FINAL REPORT

TRANSIENT HEAT TRANSFER STUDIES

Submitted to

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by

Raymond M. Hollub

Associate Project Director

UNIVERSITY OF ALABAMA BUREAU OF ENGINEERING RESEARCH

University of Alabama

University, Alabama

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FOREWORD

On February 1, 1961 NASA Contract NAS 8-1519, "The Study of Transient Heat Transfer Problems" was initiated. During the period from February 1, 1961 through September 14, 1962, one experimental test facility for obtaining heat transfer test data was designed, fabricated and calibrated. A portion of experimental data was collected to determine heat transfer coefficients in confined spaces. These results were presented in the summary report for NASA Contract Number NAS 8-1519, January 1961.

During the period from January 28, 1963 to January 28, 1965, the research effort was continued for the determination of experimental values of heat transfer coefficients in confined spaces under NASA Contract NAS 8-5217.

ACKNOWLEDGEMENT

The successful collection of experimental data presented in this report is due greatly to the effort of research associate W. H. Thrasher. The experimental techniques, the detail in organizing the system of uniform data preparation and the patience in developing reliable instrumentation by Mr. Thrasher was invaluable.

Mr. T. W. Winstead, Contract Office Representative for the George C. Marshall Space Flight Center, provided prudent counsel and guidance for developing the broad experimental program; and contributed significantly to the preparation of this final report.

ABSTRACT

An experimental program was conducted to assemble a large body of measured heat transfer film coefficients in the dead-end portion of "T" and "Y" type sections of round tube, when gas flow exists in an adjacent section.

Heat transfer film coefficients, evaluated by computer reduction of experimental test data, are presented for test sections of 1.25, 2.50 and 4.00 inches diameter. Test conditions include:

1. gas (air) temperatures from 85° to 500° F.,
2. gas flow velocities from 100 to 300 fps.,
3. angular orientation of adjacent dead-end sections from 45° (approaching stagnation) to 135° (approaching direction of flow),
4. heat transfer from gas to calorimeter,
5. heat transfer from calorimeter to gas.

Velocity measurements were made within the dead-end sections. Flow visualization was accomplished and filmed in the dead-end test sections; and gas flow behavior was described quantitatively for all geometric arrangements and test flow velocities.

Heat transfer film coefficients within the dead-end portion of

over

adjacent sections were successfully correlated with the local velocity and the free stream velocity, Reynolds Number, angular geometry and the dead-end section length.

The maximum values for heat transfer film coefficients measured within the dead-end section, and values extrapolated to the intersection of adjacent sections were all significantly less than the values calculated by accepted methods for predicting heat transfer film coefficients in straight tube walls. However, significant variation of maximum measured values of film coefficient existed with respect to the parameters identified.

Design criteria are developed for optimizing the design of "T" and "Y" sections adjacent to sections where gas flow exists, by utilizing the body of experimental data assembled.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

FINAL REPORT

TRANSIENT HEAT TRANSFER STUDIES

I. INTRODUCTION

A conservative design attitude for the development of most hardware configurations, where hot gas flow will exist in sections adjoining valves, tee's or other geometric arrangements is to obtain the highest quality parts or fittings; and assemble the configuration with a fabrication process of highest quality. If the hardware scheme proves sufficient in test evaluation, the design is generally frozen and no attempt is made to improve the configuration by optimization.

This attitude is not unusual or unique to heat transfer design problems. The study of heat transfer phenomena, particularly in the area of valves and tee's is less conventional and generally undefined; and has received little attention in basic research.

The research effort under Contract NAS 8-5217 was initiated to study heat transfer in the dead-end portion of "T" and "Y" sections, where gas flow exists in adjacent sections of the flow system. Experimental data for such geometric arrangements are presently non-existent and the research effort was directed to assemble a comprehensive body of valid heat transfer data to provide such information.

SYMBOLS

h	Experimentally determined value of Heat Transfer Film Coefficient, (BTU/hr. Ft.^{2} ^oF)
h_{avg}	Graphical average value of h (for three series A, B and C plotted on same curve), (BTU/hr. Ft.^{2} ^oF)
h_{max}	The value of the h_{avg} curve extrapolated to the intersection of the calorimeter center line with the surface of the adjoining flow through section.
γ	Geometric Parameter Angle measured between the centerlines of the flow through test section and the calorimeter. (Figure 1)
T	Calorimeter Temperature, (^oF) (Temperature reported by thermocouple)
T_o	Initial calorimeter temperature, (^oF) (Temperature at start of test)
T_∞	Free stream gas temperature, (^oF)
q	Heat transfered, (BTU/hr.)
M	Calorimeter element weight, (lbm)
A	Calorimeter element surface area, (ft.^{2})
C_p	Specific heat or heat capacity, (BTU/lb. ^oF)
S	Step Temperature ($T_\infty - T_o$), (^oF)
θ	Time, (Seconds)
V	Gas velocity in flow through section, (ft./sec.)
v	Gas velocity in dead-end test sections (ft./sec.)
D	Calorimeter internal diameter, (inches)

L	Calorimeter test section length, (inches)
N_R	Reynolds Number

TERMS

Series	A longitudinal set of calorimeter elements at a specific circumferential location, A, B, or C. (Figure 1)
Hot Test	Calorimeter heated to temperature above the free stream temperature and $(T_\infty - T_o)$ is a negative quantity.
Cold Test	Calorimeter cooled to temperature below free stream temperature and $(T_\infty - T_o)$ is a positive quantity.
Configuration	The experimental identification of the specific angular geometries analyzed. (Figure 1)

II. OBJECT OF INVESTIGATION

The principal objectives for the research effort of Contract NAS 8-5217 were:

1. To identify the principal parameters influencing the heat transfer film coefficient in dead-end sections adjacent to sections where gas flow exists,
2. To correlate the parameters identified, in a direct empirical manner.

These parameters are discussed in section III.

To accomplish the principal research objectives the scope of the experimental program was outlined to evaluate the heat transfer phenomena of interest, and the following experimental tasks were specified and discussed in section III:

1. A large body of experimental heat transfer data would be collected in order that statistical techniques could be applied to the evaluation of the test data.

2. A uniform method for the reduction and analysis of experimental data would be applied.

3. A number of different geometric arrangements, orienting the calorimeter test section to the gas flow test section, would be examined.

4. Several different diameters of test calorimeters would be used to determine size effects.

5. Velocity measurements of the gas within the calorimeter test section were to be made to provide additional experimental information related to the heat transfer coefficients.

6. Experimental efforts were to be undertaken to identify the behavior and character of gas movement within the calorimeter test section.

7. Heat transfer coefficients would be determined at a point as close to the junction of the flow through test section and the calorimeter test section as possible.

8. Experimental observations were to be carried out to quantify mass transfer effects, and make use if possible, data assembled under previous contract research efforts.

9. Elevated temperature gas flow studies would be undertaken to provide data for temperature parameter studies.

III. SUMMARY OF RESULTS

The result summary is presented in four parts identified as Heat Transfer Data and Parameters, Parameter Correlations, Design Data and Supporting Results.

A. Heat Transfer Data and Parameters

1. The heat transfer film coefficients measured with all test calorimeters varied in a characteristic curve that could be described as an exponential function of calorimeter length. Typical test data for a 2.50 inch and a 4.00 inch test section are shown in Figure II. The plotted curves are characteristic of all test data as shown in Appendix A.

2. The heat transfer film coefficients measured with all test calorimeters indicated a random variation of low magnitude with respect to the circumferential position within the calorimeter. Figure II identifies discreet values of film coefficient for specific circumferential locations plotted against increments of calorimeter length.

3. Local velocity measurements of the gas within the calorimeter test section are presented in Figure III as a function of calorimeter length. The curve is characteristic of all geometric arrangements experimentally analyzed and can be described as an exponential function of calorimeter length.

The local velocity within the calorimeter is compared with the heat transfer film coefficient within the calorimeter for identical test conditions in Figure IV. The similarity of the experimental curves indicates a correlation between film coefficient and velocity; this is discussed further in part III-D.

4. In each of the calorimeters used, regardless of the angular position of the calorimeter with respect to the section in which gas flow was maintained, the maximum value of heat transfer measured varied approximately as a linear function of the free stream test section velocity. Figure V presents the maximum heat transfer film coefficient as a function of free stream velocity for the 4.00 inch test sections, Figure VI for the 2.50 and 1.25 inch test sections.

5. The maximum heat transfer film coefficient varied in an exponential manner with the geometric parameter angle γ. Maximum values of heat transfer coefficient were measured at the parameter angle $\gamma = 45^{o}$ (approaching stagnation) and minimum values were measured at $\gamma = 135^{o}$ (approaching the direction of flow). Figure VII presents this variation of h_{max} versus γ for different free stream test section velocities. The value of h_{max} is reduced approximately by a factor of 2 (for each case shown) when the angle is varied from 45^{o} to 135^{o}.

6. The maximum heat transfer film coefficient is increased when the diameter of the test section is enlarged. Figure VIII presents h_{max} versus free stream velocity for the 4.00 inch diameter test section and the 2.50 inch diameter test section at the same parameter angle $\gamma = 90^{\circ}$.

7. The free stream temperature of the gas in the free stream test section also effects the heat transfer film coefficient. These limited data are presented in Figure IX. There is not an adequate number of experimental points to draw significant conclusions from the presentation except to point out the similar character of the (two-point) curves plotted for different velocity of gas in flow through test section.

B. Parameter Correlations

1. A reasonable correlation of maximum heat transfer film coefficient can be obtained when h_{max} is plotted as a function of Reynolds Number. Figure X presents experimental data for the 2.50 and 4.00 inch test calorimeters as a function of Reynolds Number. The geometric parameter γ is held constant and only test data for heated calorimeter is considered to avoid mass transfer effects.

Figure XI also demonstrates the good agreement of the test data as a linear function of Reynolds Number for several different values of geometric parameter γ.

2. The linear curve fits the data in Figure XI quite well and

illustrates the effect of the geometric parameter. A simple cross-correlation between h_{max}, γ and Reynolds Number can be determined by a reasonable assumption that the slopes of the curves in Figure XI are equal. This can be developed as follows:

(a) Intercept values of h_{max}, corresponding to Reynolds Number equal zero, are obtained from Figure XI and identified as h_{max_o}. These intercept values of h_{max} are plotted versus γ (measured in radians).

(b) The curve of h_{max_o} versus γ is approximately linearized by plotting $(h_{max_o})^{1/3}$ versus γ as shown in Figure XII.

(c) The linearized curve of h_{max_o} versus γ is described quantitatively as,

$$(h_{max_o})^{1/3} = 2.70 - (2.50/\pi)(\gamma) \qquad \text{Equatin 1}$$

(d) Rewriting Equation 1 yields,

$$h_{max_o} = \left[2.70 - (2.5/\pi)(\gamma)\right]^3$$

(e) Referring to Figure XI, the equation describing the family of curves for the 2.50 calorimeters is,

$$h_{max} = h_{max_o} + 4.44\,(NR)\,(10^{-5}) \qquad \text{Equation 2}$$

(f) Substituting for h_{max_o} yields,

$$h_{max} = \left[2.70 - (2.5/\pi)(\gamma)\right]^3 + 4.44\,(NR)(10^{-5})$$

This relationship can now be used to obtain h_{max} provided γ and Reynolds Number are specified. However, this is an emprical derivation and the application would be limited to the range of variables considered in the experimental data used to obtain the correlation.

In this example, for a 2 1/2 inch diameter section, with calorimeter heating the equation will predict h_{max} at the interface of two adjoining sections for materials and test conditions similar to the ones used to obtain the test data.

The Reynolds Number and geometric parameter γ were sufficient to describe the complete range of test conditions carried out in the experimental program for contract NAS8-5217. However, other parameters such as mass transfer and enthalpy potential could have significant influence on values of heat transfer coefficient obtained in a similar manner. In the examples cited, these quantities were held constant.

C. Design Data

1. The comparison of experimental h_{max} (for any geometric arrangement of dead-end adjoining section) with values of h predicted by the McAdams equation for forced convection in straight round tubes indicate that the McAdams equation is conservative. This comparison is displayed in Figures XIII, XIV and XV. It is noted that mass transfer effects are not accounted for in the McAdams equation and the comparisons are made only with experimental data for which mass transfer is negligible. The envelope curve describing McAdams values for h_{max} in Figures XIII and XV include the temperature range of data analyzed in hot and cold tests. The derivation and sample computations are presented in Appendix B on pages B-20, B-21.

In each of the Figures XIII, XIV and XV, the values of h_{max} predicted using the McAdams method is almost twice the values of h_{max} measured by experiment.

This comparison indicates that the McAdams equation can be readily applied for predicting conservative values for heat transfer film coefficient for "T" and "Y" type sections, where gas flow occurs in an adjacent section.

2. Useful design information can be generated from the experimental curves of heat transfer film coefficient versus calorimeter length or a non-dimensional (L/D) parameter.

Figure II exhibits two curves that are characteristic of all the experimental data generated under research Contract NAS8-5217. The dotted line, superimposed on the h versus calorimeter position curves, has design value when constructed in the following manner. A straight line is drawn through two points; one at h_{max} corresponding to the position locating the intersection of the calorimeter and free stream test section, the other at h = 0 corresponding to the position at L = 5 diameters, or (L/D) = 5. It can be demonstrated with each data set in Appendix A, that all experimental values of h fall beneath this dotted line.

This device is therefore a useful mechanism for predicting a conservative film coefficient at any position in geometric arrangements. In fact, a conservative description of heat transfer film coefficient distribution in adjoining sections can be predicted by using a value of h predicted by the McAdams Formula in place of h_{max}; and extrapolating the value to zero at 5 diameters within the dead-end section.

The variation of heat transfer film coefficient within the calorimeter test section could be described as an exponential function of calorimeter length. The maximum value occurring at the intersection of the adjoining sections and approaching a value comparable to the free convection film coefficient at a distance of approximately 5 diameters from the intersection.

D. Supporting Results

The general experimental results, observations and analyses of data in support of the principal objectives of the research effort are summarized as follows:

1. Experimental Data Collected

An extensive body of more than 3,000 experimental heat transfer data sets were accumulated, analyzed and reduced to provide the tabular and graphical results presented in Appendix A. The graphical results plot the value of film coefficient as a function of the position within the calorimeter where the value was measured.

A portion of the experimental data collected by the earlier research effort (Contract NAS8-15) were re-examined experimentally under similar test conditions. Test results for these data could not be duplicated or reproduced within reasonable experimental accuracy. These data are included in Appendix A but were not used in any correlation or parameter analyses. Further discussion of these data is included in section IV.

2. Data Reduction

A method was derived for the uniform, objective reduction of all experimental heat transfer data. The statistical technique, using the method of least squares, was applied in a manner that permitted the reduction of all data by digital computer. The complete body of experimental data collected under contract NAS8-1519 and NAS8-5217 were reduced by computer.

The method is derived and sample calculations for arbitrary data sets are presented in Appendix B. Comparative curves, plotting values of film coefficient determined by computer and values of film coefficient determined by graphical interpretation as a function of position within the calorimeter, are presented as Figure B-1

3. Geometric Configurations

Geometric arrangements of the dead-end calorimeter test section with respect to the free stream flow through test section were analyzed experimentally for parameter angles, $\gamma = 45^o$, 75^o, 90^o, 105^o, and 135^o as shown in Figure I. The longitudinal series of calorimeter elements (A, B and C) were always oriented in the same position with respect to the gas flow.

Experimental data were assembled for three diameters of test sections and calorimeters. The 4.00 inch test sections were oriented in the five geometric configurations described in Figure I. The 2.50 inch test sections were oriented for three geometric parameter angles $\gamma = 45^o$, 90^o and 135^o. The 1.25 inch test section was examined only at the $\gamma = 90^o$ configuration. The summary of test conditions analyzed experimentally is presented in Appendix A.

4. Local Velocity Measurements

Velocity measurements of the gas within the calorimeter test section were successfully accomplished by the use of a hot wire anemometer. A large body of local velocity measurements was assembled for the 4.00 inch diameter test section at geometric parameter angles $\gamma = 45^o$, $\gamma = 75^o$ and $\gamma = 105^o$. This information was presented in graphical form in Monthly Progress Reports.

From the flow visualization studies, useful engineering information was obtained from the body of experimental local velocity measurements that had been assembled. The average circumferential velocity was computed at each station corresponding to a reporting thermocouple. The resulting average circumferential velocities were plotted against the calorimeter length. With the hot wire anemometer probe, it was possible to extend the measurements of gas velocities to the intersection of the calorimeter test section and the free stream flow through test section. These results are presented in Appendix D.

5. Gas Flow Patterns in Calorimeter Test Section

The behavior of the gas flow within the calorimeter test section was clearly identified by the flow visualization experiments attempted. A fine suspension of ammonium chloride was generated within a transparent dead-end section that had been substituted for the calorimeter test section. The flow patterns of the gas within the dead-end test section were distinctly identified at all gas velocities within the free stream test section. The experiments indicated that a vortex was generated along the length of the calorimeter test section. The nature of the gas behavior within the calorimeter test section was essentially circumferential. This behavior was similar for all free stream test section gas velocities, for all configurations.

High speed motion picture photographs were made of the flow patterns in order that the mechanism of flow could be observed as closely as possible. The film record was exhibited to the contract representatives at a conference meeting during the contract period.

In addition to defining the behavior of the gas within the calorimeter test section, the flow visualization made possible a quantitative correlation between heat transfer coefficient and gas velocity within the calorimeter test section. Calculations of average local velocity within the calorimeter are presented in Appendix D.

6. Extrapolation of Heat Transfer Data

Heat transfer film coefficients at the intersection of the calorimeter test section and the free stream flow through test section were determined implicitly from the hot wire anemometer velocity measurements. This was accomplished by correlating the heat transfer coefficient along the calorimeter test section to the gas velocity within the calorimeter test section. These results, presented in Figure IV indicate a very good point for point graphical correlation of film coefficient with average circumferential gas velocity within the calorimeter test section. Since the gas velocities could be measured directly to the intersection, and because the film coefficient varied directly with the velocity, the confidence in extrapolating the average heat transfer coefficient curve versus calorimeter length to the intersection was justified. This extrapolated value was identified as h_{max}.

The confidence in the quantitative values for h_{max} was reinforced by evaluating all parameters at a reference point, two diameters within the calorimeter test section. These tabular data of h_{avg} at 2 diameters are presented as Table IV and exhibit graphical displays similar to h_{max} when plotted for parametric studies.

7. Mass Transfer

To determine mass transfer effects, the direction of heat transfer in the calorimeter test section was reversed. This was accomplished by heating the calorimeter to a temperature above the ambient free stream temperature of the gas in the flow through test section. The experimental results indicate that mass transfer effects did exist in all heat transfer data collected in tests where the calorimeter was cooled below the ambient free stream temperature of the gas flow in the 4.00 and 2.50 inch facility. The quantity of heat transferred via the mass transfer mechanism was significant and varied somewhat with the ambient environment. Comparative curves of average heat transfer film coefficient versus calorimeter length for hot and cold tests are presented in Figures A-125 through A-130. Further discussion is included in section IV.

Mass transfer effects in the 1.25 inch hot gas facility was negligible because the air supplied to the heater section from the storage tank had been chemically dried to a moisture content of less than one percent. By comparison, the air recirculated in the 4.00 and 2.50 test facility was near saturation due to leakage in the water cooled heat exchangers.

Mass transfer effects were eliminated from the parameter correlations by considering only those data collected in hot tests.

IV. DISCUSSION OF RESULTS

A. Experimental Data

Approximately three-thousand-five-hundred data sets were developed experimentally in the research effort under NAS8-5217. The design, fabrication and adoption of the multi-channel Visicorder permitted 12 simultaneous measurements of reporting thermocouples. The time saved in data collection permitted a broader range of experiments to be attempted. In addition, the fabrication of a switching, calibrating and reference junction monitor precluded the continuing task of hand fastening each thermocouple lead to the X-Y recorder to obtain one bit of information. The confidence in the instrumentation is demonstrated by the results described in Figures A-76 through A-79. Identical test conditions were executed 30 days apart and heat transfer data was collected on both occasions; the graphical presentations demonstrate the ability of the test facilities to duplicate data.

Data collected under contract NAS8-1519 (Tables A-31 through A-45) could not be confirmed by repeating the test conditions. These data presented in the final report for NAS8-1519 indicate h_{max} values in excess of 100 (BTU/HR-FT^2 - ^oF), these values could not be validated, and were not used in any correlation effort. Mass transfer effects, questionable instrumentation and experimental procedures could easily have contributed to the high values interpreted from experimental efforts.

B. Mass Transfer

The early research effort under contract NAS8-1519 precluded that mass transfer effects were negligible. The absence of detectable condensation on the inside calorimeter surface was used to support for this assumption.

Suspecting enthalpy potential and condensate amounts too small to be determined by hand, the direction of heat transfer was reversed in the experimental program of contract NAS8-5217. The startling results, shown in comparative graphical form as Figures A-125 through A-130 revealed that mass transfer effects were very significant. No further attempt was made to pursue experimental programs where mass transfer was possible.

No consistent behavior could be determined for the measured mass transfer; except to provide reasonable quantitative measure of gas inter-change between the flow-through test section and the dead-end test section. However, no effort was developed to explore these data further.

The heat transfer measurements in the 1.25 inch test facility were conducted for one geometric configuration $\gamma = 90^{\circ}$. Although the tests accomplished were cold tests by definition $(T_{\infty} - T_{o})$ a positive quantity, mass transfer effects were assumed to be negligible. The air, heated and forced through the test section had been passed through a chemical dryer and provided air with a moisture content of less than 1/2 of 1 percent. The free stream air temperature and calorimeter test temperature were far above the temperature at which mass transfer could take place.

C. Local Velocity Measurement

The velocity measurements within the calorimeter test section by hot-wire anemometer are described in this report for three geometric arrangements, $\gamma = 45^{\circ}$, $\gamma = 75^{\circ}$ and $\gamma = 105^{\circ}$. No attempt was made to obtain local velocity measurements for all test configurations examined because of the time required to make a creditable measurement survey. More than 400 discreet measurements were necessary to establish the velocity distribution within the calorimeter test section for one free stream velocity. The three configurations analyzed, required 6,000 experimental measurements.

A carefully designed experimental technique is necessary to obtain valid quantitative data with a hot-wire anemometer.

D. Recommendations

The spectrum of test data assembled in this report has provided some useful design criteria which can be applied to the problems of heat transfer from gas flow near valves and other geometric arrangements. The collection of large quantiites of additional experimental data would not provide much additional design data of value. Parameters such as surface roughness, different diameters in test sections and others would provide interesting results but the probability of determining new and significant design data is obscure.

Two areas of further experimental study are recommended.

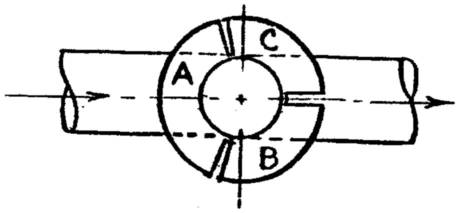
1. High Temperature Heat Transfer Measurements

The experimental techniques that would be developed in this program would be of value. The temperature range should approach $1500^{\circ}F$.

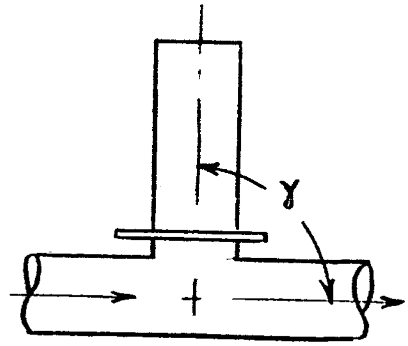
2. Flow Mechanism Studies

The flow visualization experiments indicate a possibility for a mathematical development to describe the behavior of gas flow in the vicinity of dead-end sections. The consistent generation of the vortex for all test conditions prompts the recommendation. A mathematical development could be verified with the experiment test facilities and instrumentation developed for NAS8-5217.

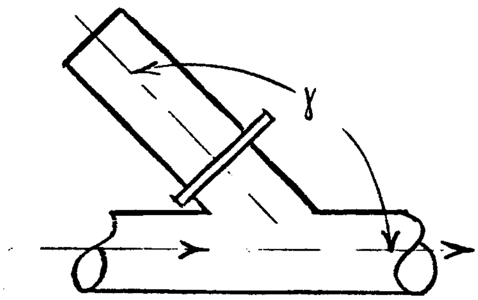
The experimental and theoretical program could be generated to make optimum use of the existing test facilities, instrumentation and refined experimental techniques to develop peripheral studies of interest to high temperature heat transfer problems and gas flow phenomena.



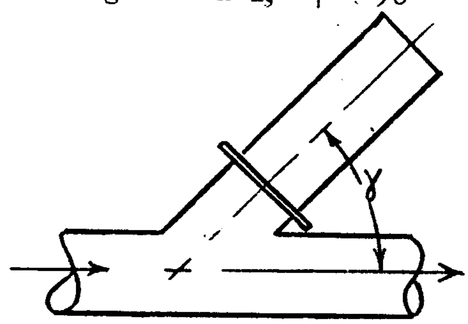
Calorimeter Series Arrangement



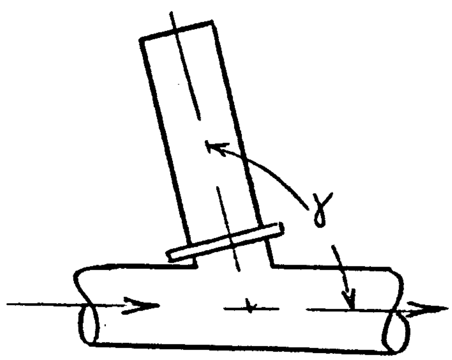
Configuration 1, $\gamma = 90^{\circ}$



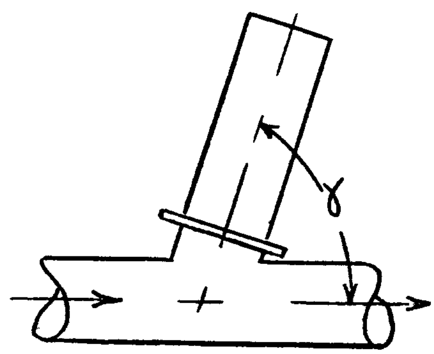
Configuration 2, $\gamma = 135^{\circ}$



Configuration 3, $\gamma = 45^{\circ}$



Configuration 4, $\gamma = 105^{\circ}$



Configuration 5, $\gamma = 75^{\circ}$

Figure 1 Experimental Configuration Geometry

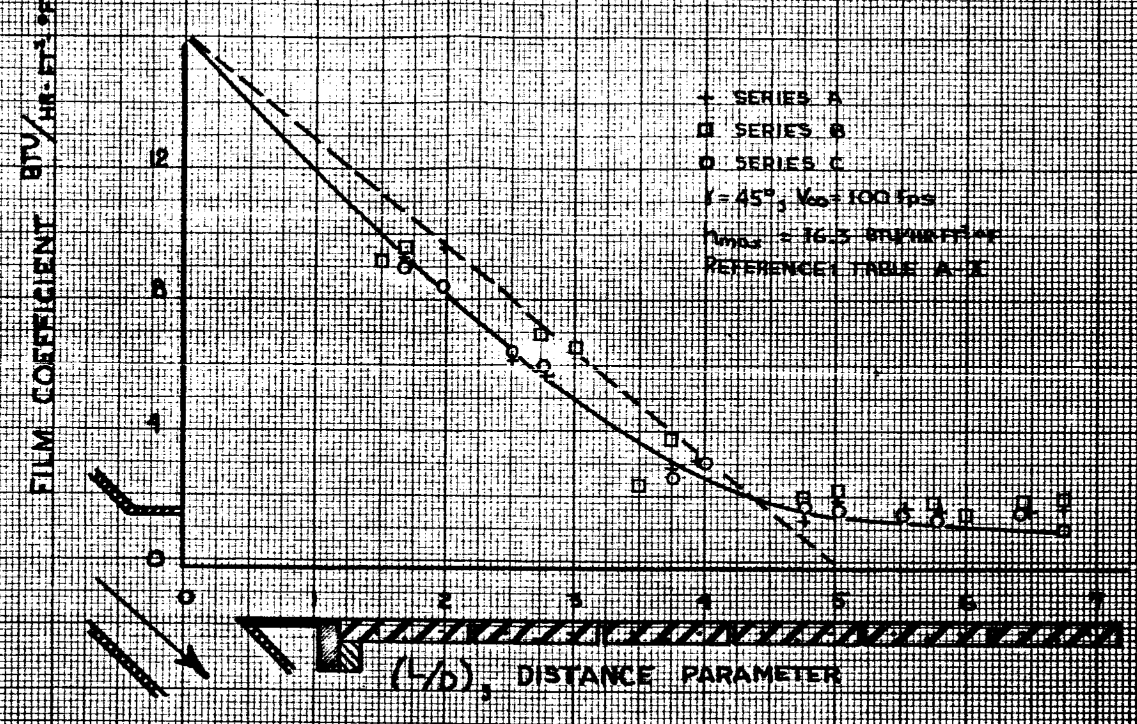


FIGURE II, FILM COEFFICIENT FOR 2.50 INCH SECTION

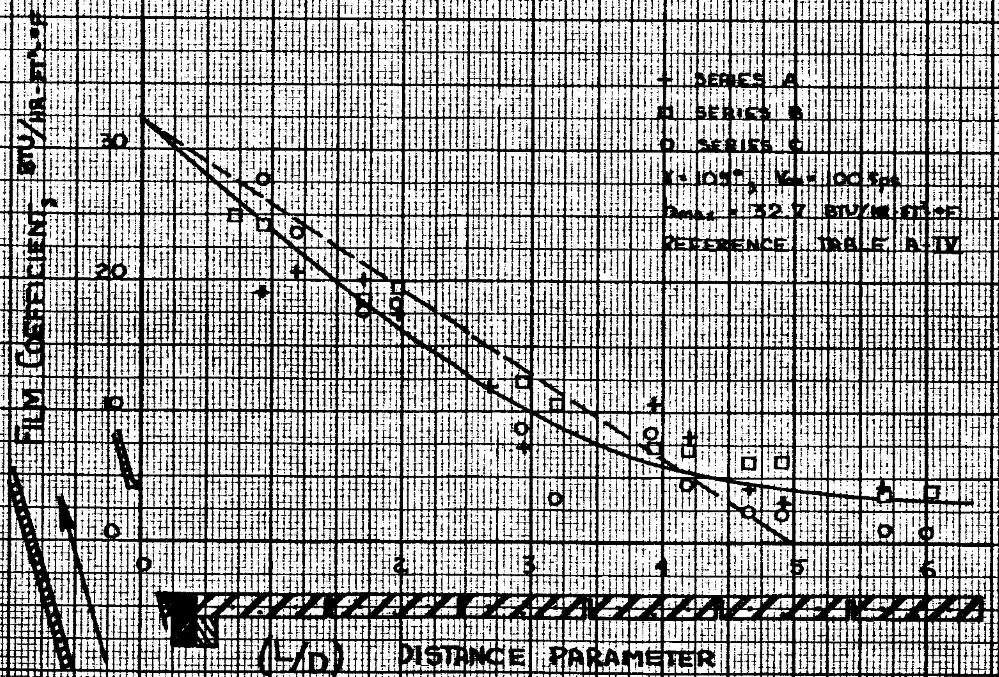


FIGURE II, FILM COEFFICIENT FOR 4.00 INCH SECTION

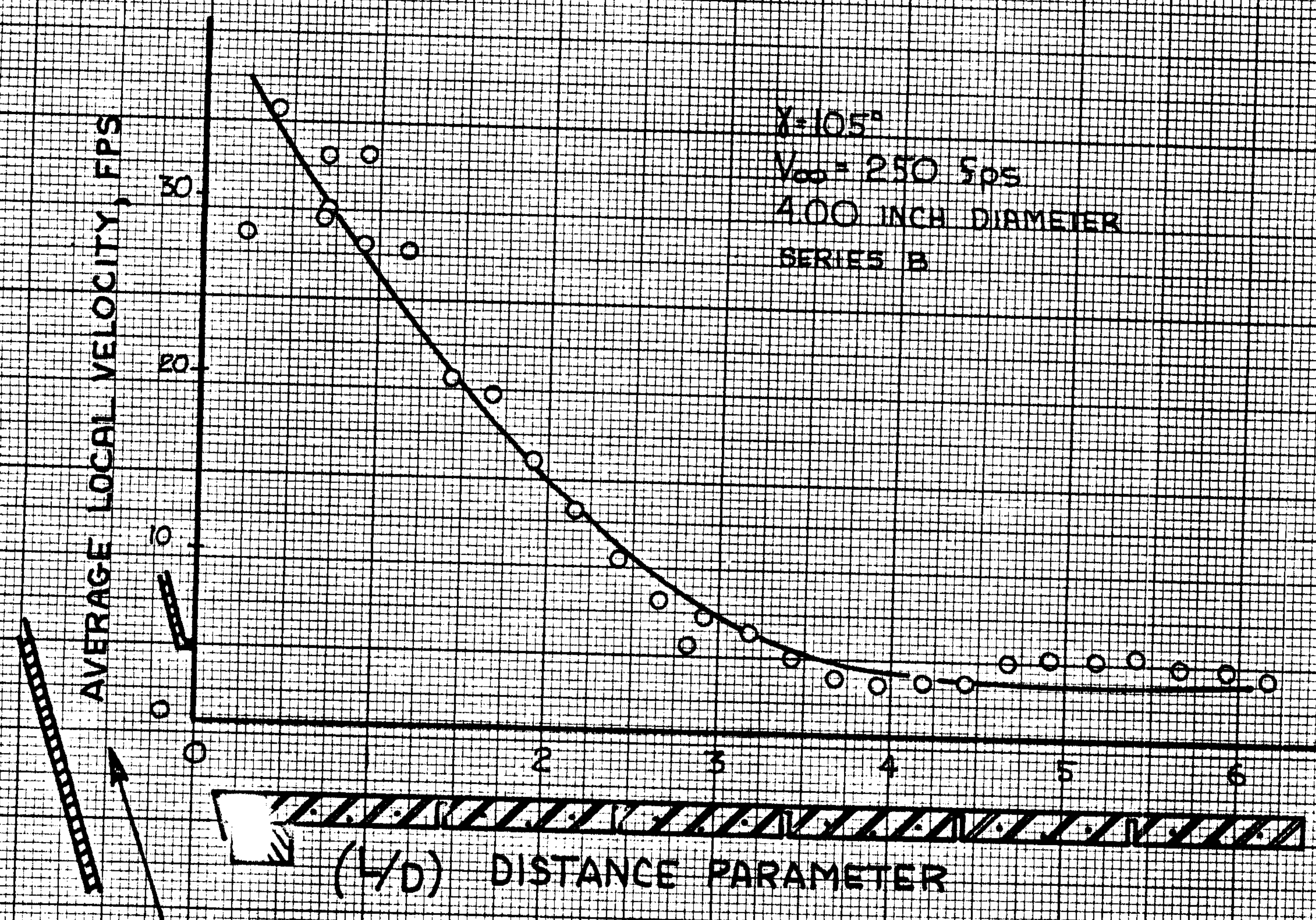


FIGURE III, LOCAL VELOCITY VERSUS CALORIMETER POSITION

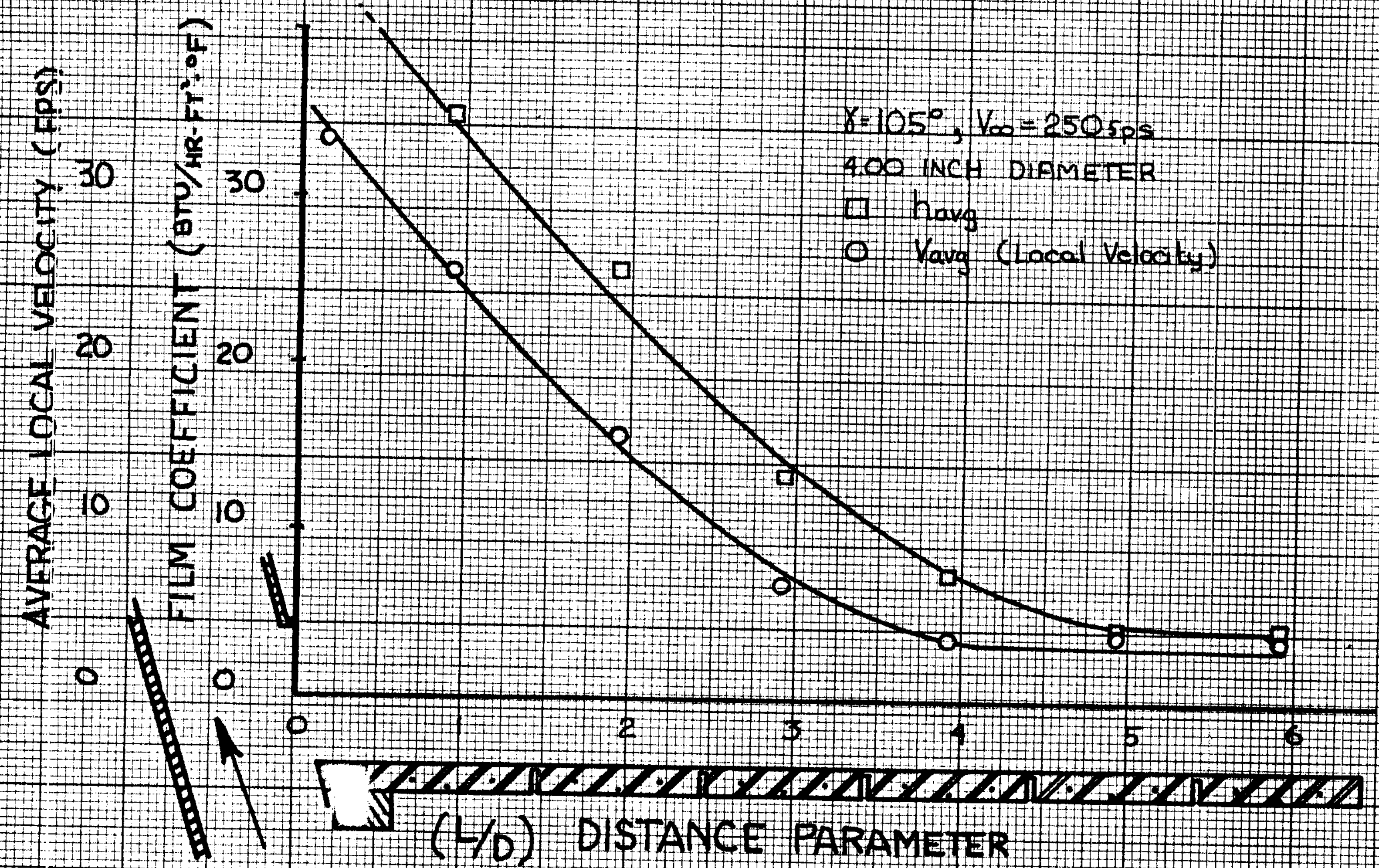


FIGURE IV, FILM COEFFICIENT AND LOCAL VELOCITY, TYPICAL COMPARISON VERSUS CALORIMETER POSITION

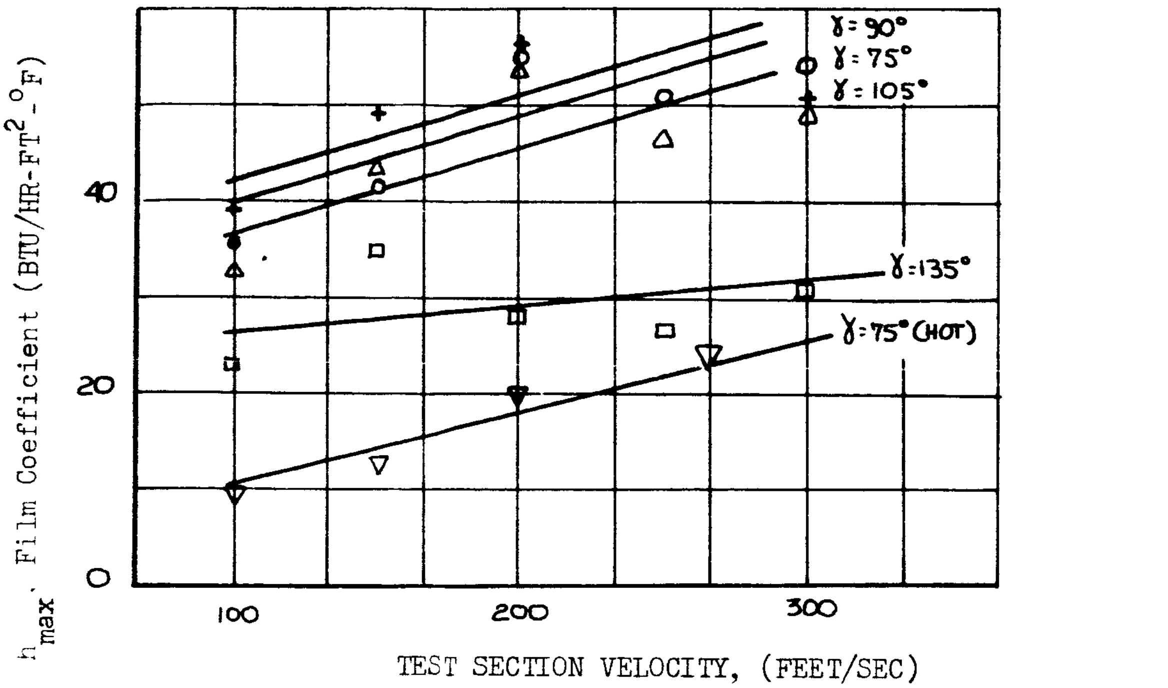


FIGURE V Film Coefficient Versus Velocity For 4 Inch Diameter Test Sections at Various γ

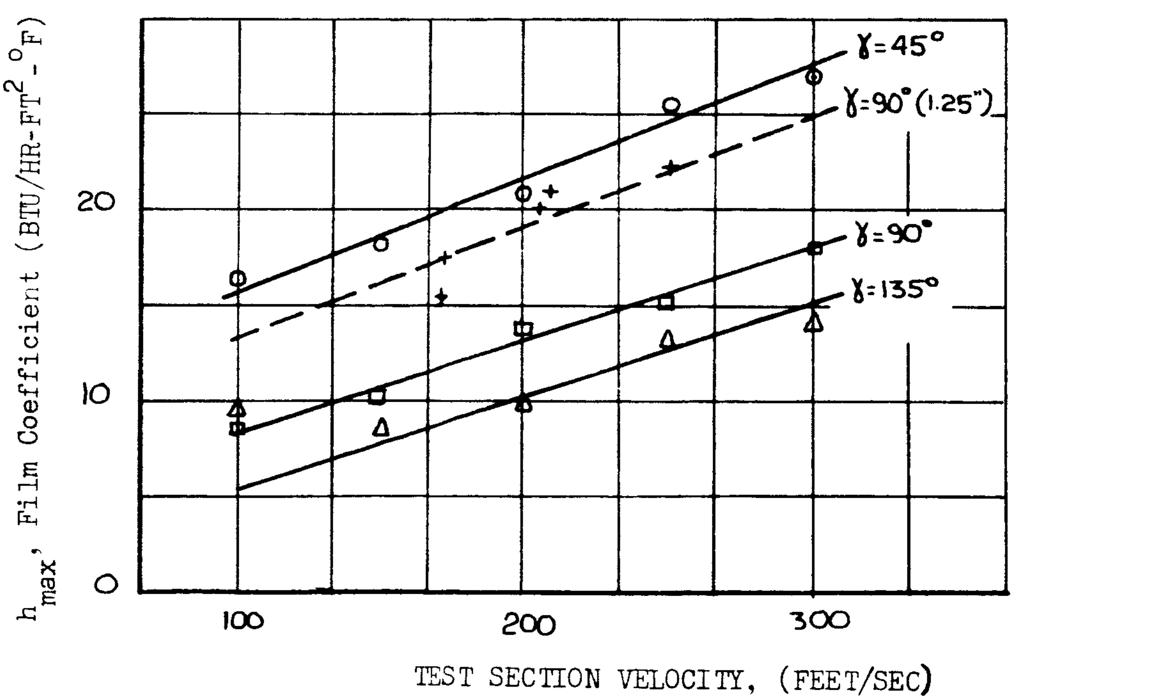


FIGURE VI Film Coefficient versus Velocity for 2.50 inch and 1.25 inch Test Sections at Various γ

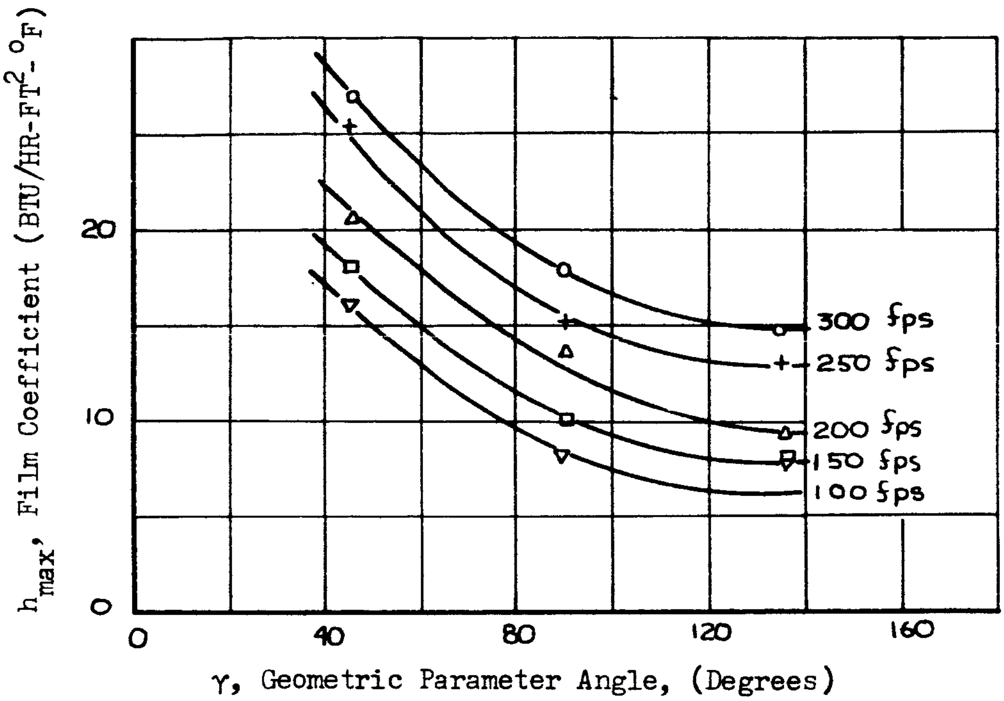


FIGURE VII Film Coefficient Versus Parameter Angle, γ (2.50 Inch Diameter Test Section)

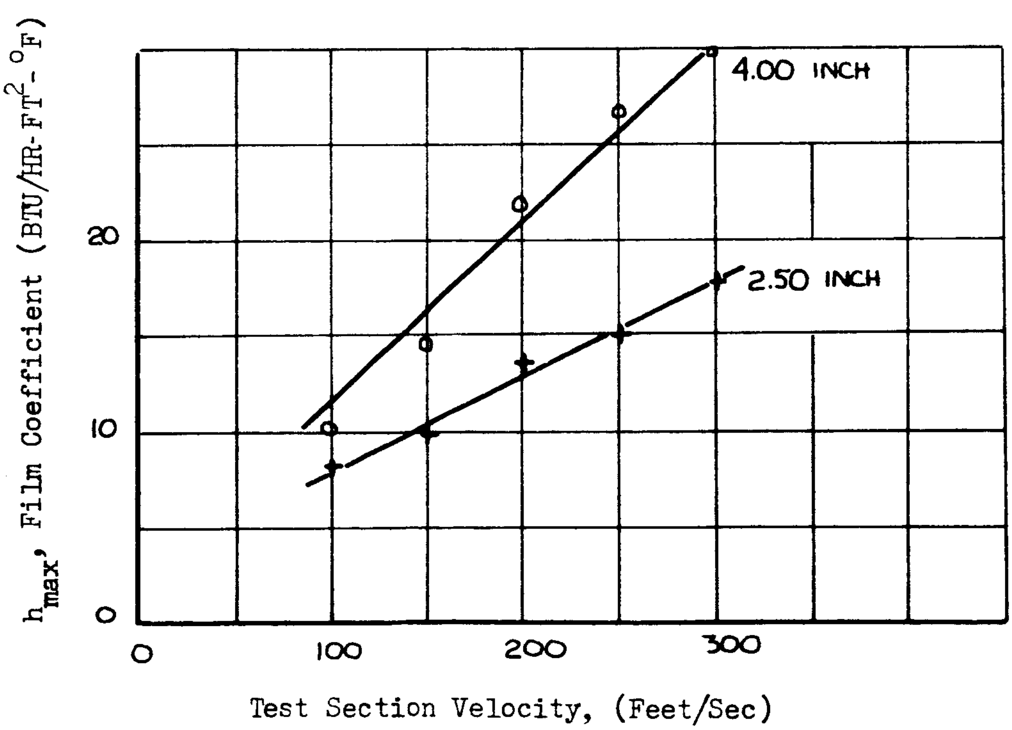


FIGURE VIII Film Coefficient Versus Velocity, ($\gamma = 90^o$)

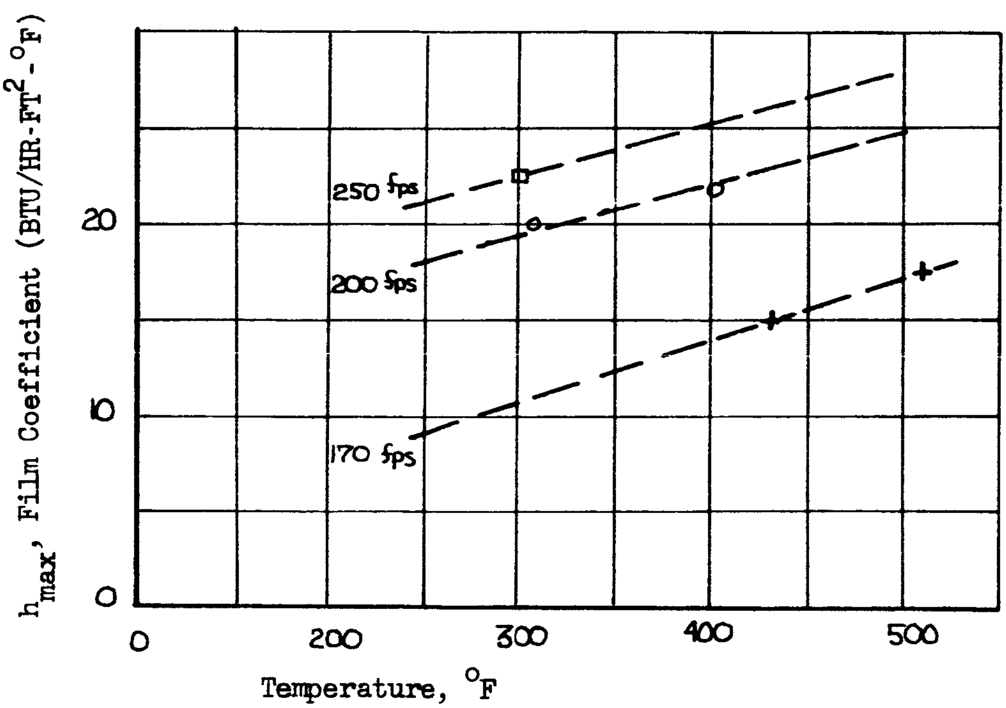


FIGURE IX Film Coefficient Versus Temperature, ($\gamma = 90^\circ$; 1.25 Inch Test Section at Various Velocities)

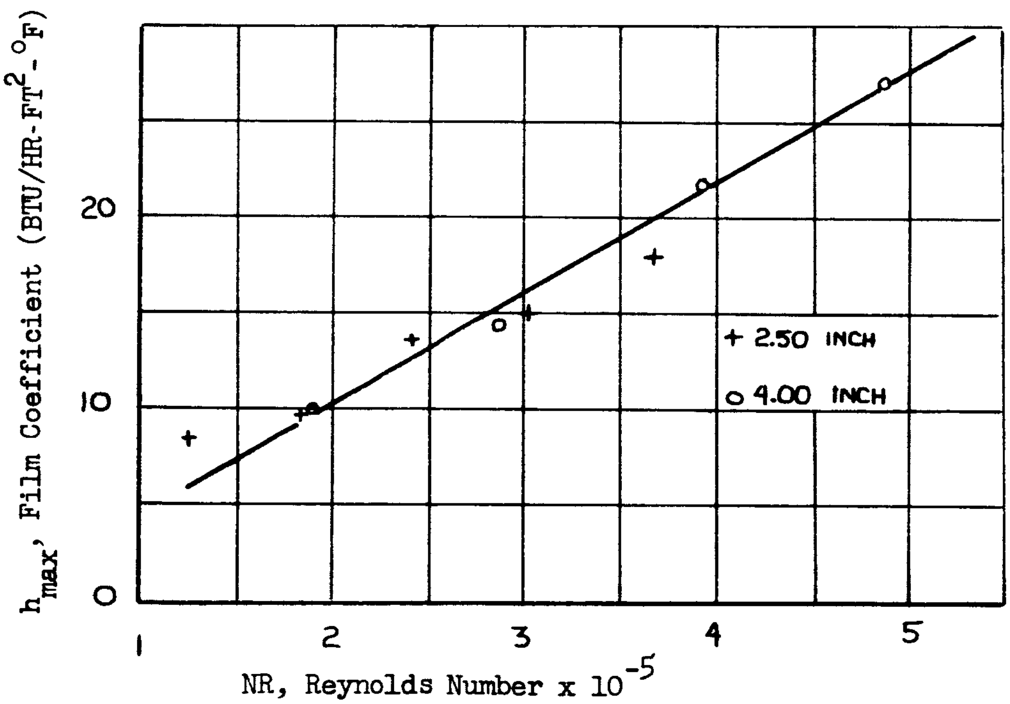


FIGURE X Film Coefficient versus Reynolds Number Correlation, ($\gamma = 90^\circ$ For 2.50 Inch and 4.00 Inch Diameters)

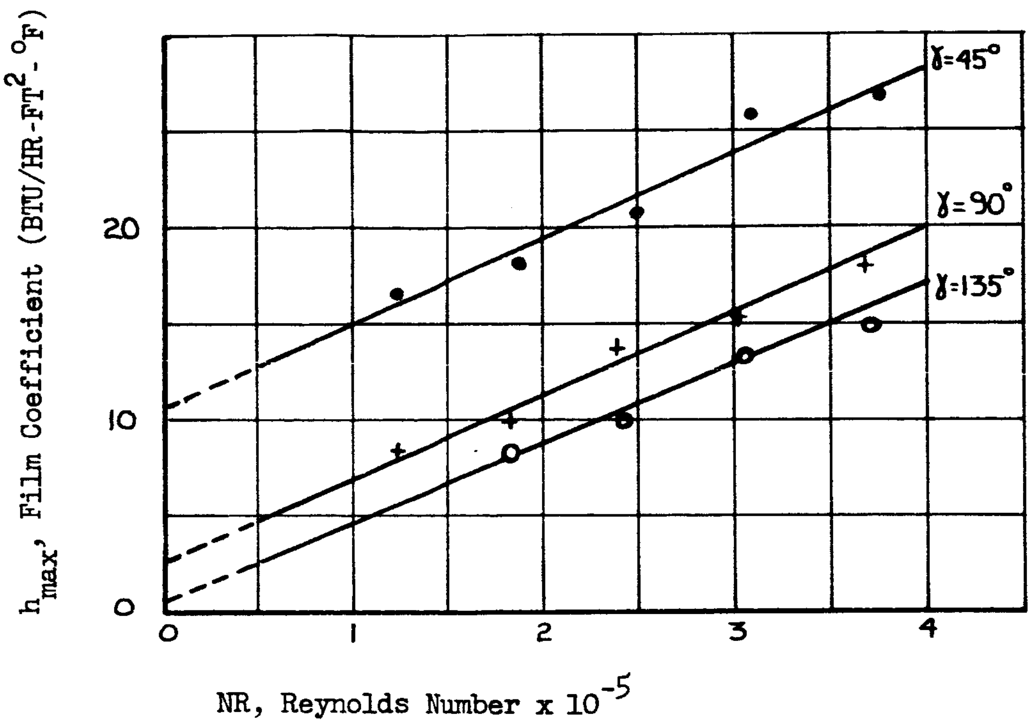


FIGURE XI Film Coefficient Versus Reynolds Number For Various γ (2.50 Inch Diameter Test Section)

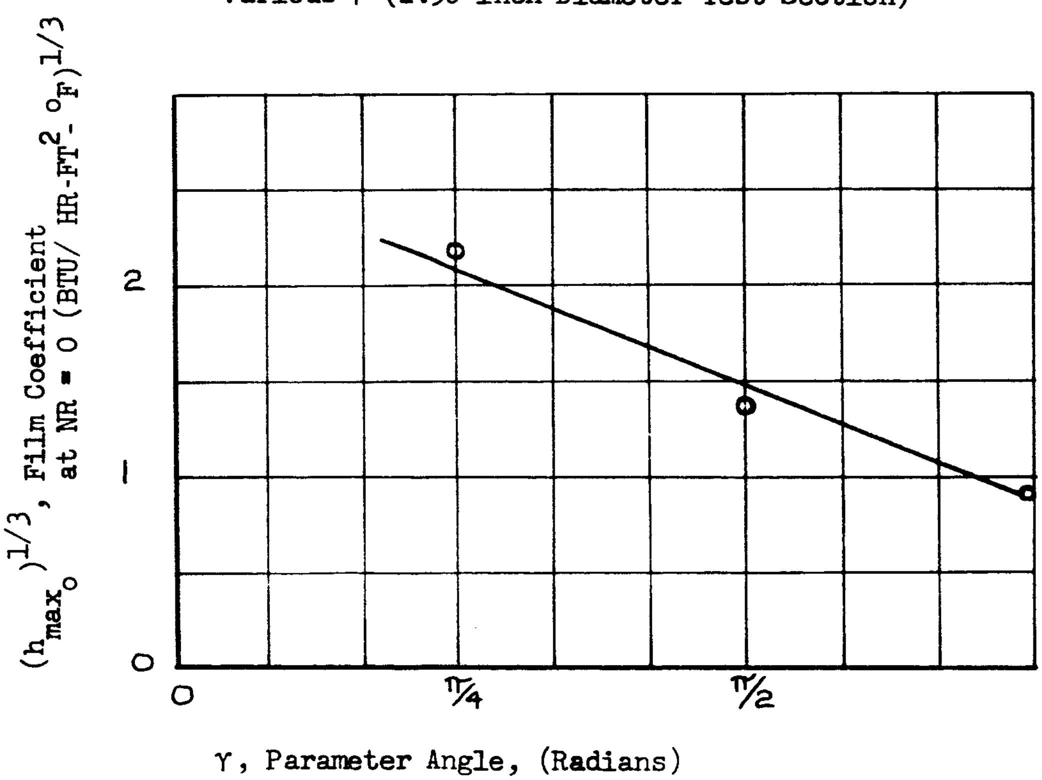


FIGURE XII Correlation of Film Coefficient with Geometric Parameter Angle for 2.5 Inch Diameter Section

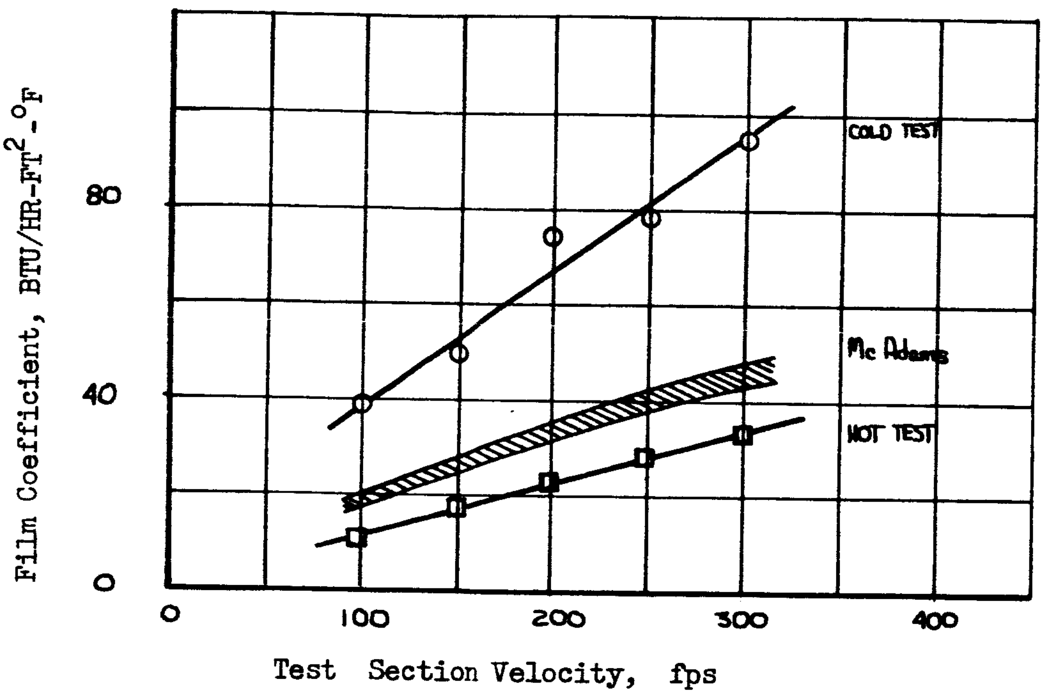


Figure XIII, Comparison of Mc Adams Equation Range with 4.00 Inch Diameter Test Data For $\gamma = 90^o$

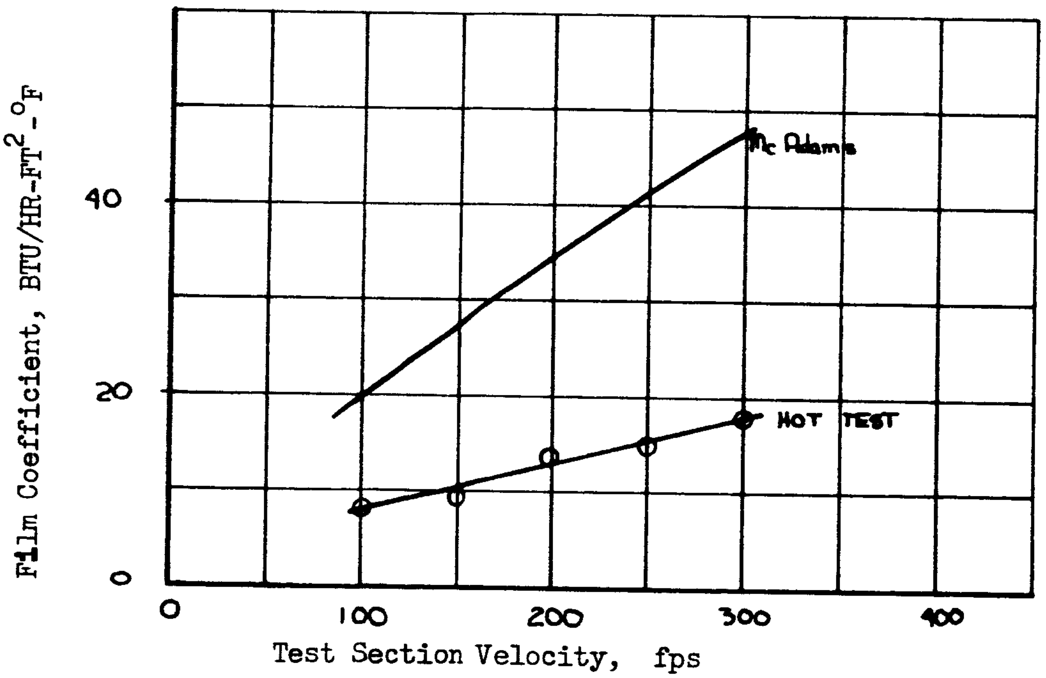


Figure XIV, Comparison of Mc Adams Equation with 2.50 Inch Diameter Test Data For $\gamma = 90^o$

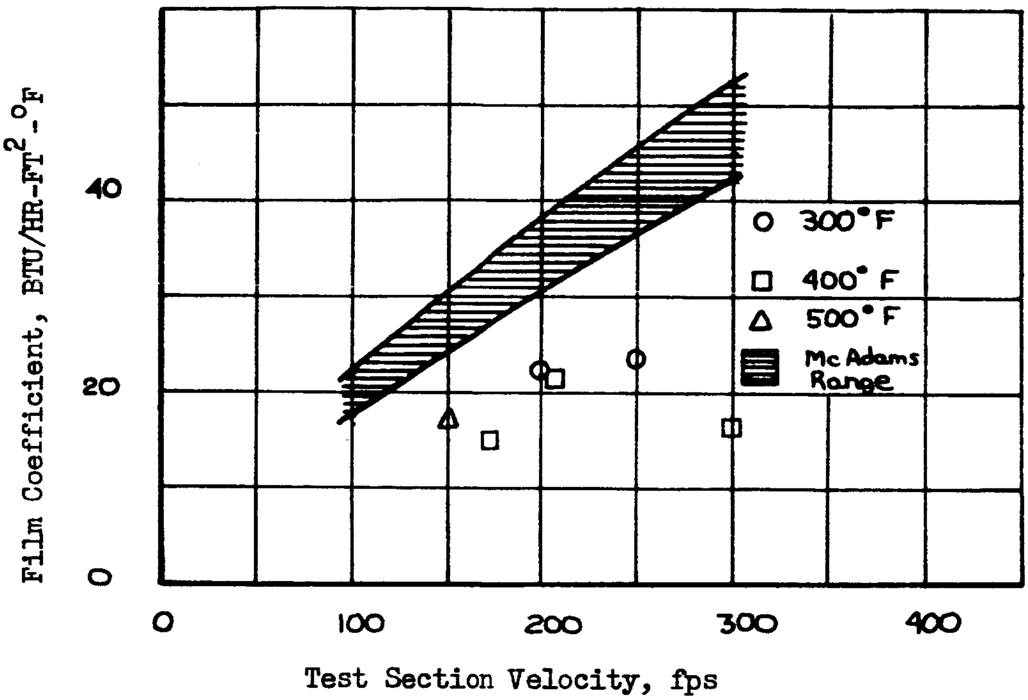


Figure XV, Comparison of Mc Adams Equation Range with 1.25 Inch Diameter High Temperature Data for $\gamma = 90^\circ$

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TABLE I

TABULAR VALUES OF MAXIMUM HEAT TRANSFER FILM COEFFICIENT

for

4 Inch Diameter Test Sections

$\gamma = 45^{o}$, (Positive Step Temperature)

Velocity	100 fps	150 fps	200 fps	250 fps	300 fps
Reynolds No.	1.95×10^5	2.81×10^5	3.72×10^5	4.58×10^5	5.42×10^5
h_{max} (A)	11.8	47.8	15.2	9.0	7.6
(B)	35.6	19.7	14.6	10.8	13.2
(C)	12.2	3.8	23.8	11.2	8.3
Average	19.8	23.8	17.8	10.3	9.7

$\gamma = 75^{o}$, (Positive Step Temperature)

Reynolds No.	1.91×10^5	2.85×10^5	3.84×10^5	4.63×10^5	5.38×10^5
h_{max} (A)	23.5	29.1	40.0	39.5	42.5
(B)	42.5	47.4	63.0	56.4	58.8
(C)	38.8	47.0	66.0	57.0	60.5
Average	34.9	41.2	52.3	51.0	53.9

$\gamma = 90^{o}$, (Positive Step Temperature)

Reynolds No.	1.89×10^5	2.91×10^5	3.67×10^5	4.25×10^5	5.04×10^5
h_{max} (A)	34.8	41.6	65.6	105.0	83.2
(B)	45.0	58.2	80.0	61.5	102.5
(C)	36.8	47.6	82.4	72.0	103.0
Average	38.8	49.2	76.0	79.4	96.0

TABLE I cont'd

TABULAR VALUES OF MAXIMUM HEAT TRANSFER FILM COEFFICIENT

For

4 Inch Diameter Test Sections

$\gamma = 105^{o}$, (Positive Step Temperature)

Velocity	100 fps	150 fps	200 fps	250 fps	300 fps
Reynolds No.	1.99×10^5	2.91×10^5	3.90×10^5	4.81×10^5	5.66×10^5
h_{max} (A)	29.4	32.8	50.7	44.2	48.5
(B)	31.6	43.5	43.0	43.5	45.6
(C)	37.2	51.5	63.0	51.3	53.0
Average	32.7	42.6	52.2	46.3	49.0

$\gamma = 135^{o}$, (Positive Step Temperature)

Reynolds No.	1.93×10^5	2.88×10^5	3.73×10^5	4.67×10^5	5.42×10^5
h_{max} (A)	24.0	60.0	39.4	31.0	38.1
(B)	22.0	21.7	28.7	24.8	19.2
(C)	23.0	28.7	31.8	25.5	33.6
Average	23.0	36.7	33.3	27.1	30.3

$\gamma = 75^{o}$, (Negative Step Temperature)

Reynolds No.	1.98×10^5	2.91×10^5	3.90×10^5	4.81×10^5	5.65×10^5
h_{max} (A)	8.2	11.0	16.1	17.0	26.7
(B)	8.9	11.5	20.7	28.2	22.6
(C)	10.9	13.8	24.7	28.2	40.0
Average	9.4	12.1	20.5	24.4	29.8

TABLE I cont'd

TABULAR VALUES OF MAXIMUM HEAT TRANSFER FILM COEFFICIENT

for

4 Inch Diameter Test Sections

$\gamma = 90^{\circ}$, (Negative Step Temperature)

Velocity	100 fps	150 fps	200 fps	250 fps	300 fps
Reynolds No.	1.88×10^5	2.88×10^5	3.94×10^5	4.86×10^5	5.73×10^5
h_{max} (A)	11.5	10.1	17.5	23.2	25.4
(B)	10.8	16.0	23.5	28.5	33.0
(C)	12.0	13.8	26.2	26.1	31.0
Average	10.1	14.5	22.0	27.0	32.5

$\gamma = 90^{\circ}$, (Positive Step Temperature) Repeat Runs

Velocity	200 fps	300 fps
Reynolds No.	3.81×10^5	5.91×10^5
h_{max} (A)	49.6	37.0
(B)	59.0	47.5
(C)	69.0	53.0
Average	56.0	49.0

TABLE II

TABULAR VALUES OF MAXIMUM HEAT TRANSFER FILM COEFFICIENT

For

2.5 Inch Diameter Test Section

$\gamma = 45^{o}$, (Negative Step Temperature)

Velocity	100 fps	150 fps	200 fps	250 fps	300 fps
Reynolds No.	1.22×10^5	1.89×10^5	2.46×10^5	3.09×10^5	3.72×10^5
h_{max} (A)	18.4	19.4	24.0	20.8	18.4
(B)	16.5	21.3	20.0	27.6	17.6
(C)	16.8	16.6	19.0	18.2	14.2
Average	16.3	18.0	20.6	25.6	27

$\gamma = 90^{o}$, (Negative Step Temperature)

Reynolds No.	1.22×10^5	1.81×10^5	2.38×10^5	3.01×10^5	3.66×10^5
h_{max} (A)	8.4	9.6	13.6	12.2	18.0
(B)	7.0	8.4	15.4	18.2	17.6
(C)	7.6	9.5	12.5	14.0	16.2
Average	8.4	9.8	13.8	15.0	17.9

$\gamma = 135^{o}$, (Negative Step Temperature)

Reynolds No.	1.25×10^5	1.81×10^5	2.41×10^5	3.04×10^5	3.70×10^5
h_{max} (A)	10.2	6.7	7.6	12.8	15.7
(B)	7.8	6.2	8.0	11.8	15.2
(C)	7.6	7.8	11.0	14.0	14.8
Average	9.3	8.4	9.4	13.1	14.6

TABLE III

TABULAR VALUES OF MAXIMUM HEAT TRANSFER FILM COEFFICIENT

For

1.25 Inch Diameter Test Section at Elevated Temperatures

$\gamma = 90^\circ$, (Positive Step Temperature)

Velocity	170 fps	172 fps	212 fps	208 fps	244 fps	292 fps
Reynolds No.	3.78×10^4	4.42×10^4	5.76×10^4	6.99×10^4	8.27×10^4	8.01×10^4
Temperature	506°F	429°F	401°F	303°F	300°F	397°F
h_{max} (A)	16.0	14.0	20.6	19.6	20.6	14.0
(B)	18.9	13.4	20.9	19.4	21.4	15.2
(C)	16.4	14.6	21.4	20.5	20.4	13.0
Average	17.2	15.0	21.0	20.2	22.4	14.6

TABLE IV

TABULAR VALUES OF AVERAGE HEAT TRANSFER FILM COEFFICIENT
MEASURED AT DISTANCE OF 2 DIAMETERS FROM THE
FREE STREAM SURFACE - WITHIN THE CALORIMETER
for
4 Inch Diameter Test Sections
$\gamma = 45^{o}$ (Positive Step Temperature)

Velocity		100 fps	150 fps	200 fps	250 fps	300 fps
Reynolds No.		1.95×10^5	2.81×10^5	3.72×10^5	4.58×10^5	5.42×10^5
h_{max}	(A)	7.5	26.0	9.2	4.8	5.0
	(B)	20.8	12.0	9.3	5.5	7.7
	(C)	7.5	2.7	12.5	5.8	5.0
Average		12.0	13.6	10.3	5.3	5.9
$\gamma = 75^{o}$ (Positive Step Temperature)						
h_{max}	(A)	15.7	19.8	27.0	27.0	28.5
	(B)	22.0	26.4	34.5	33.0	34.8
	(C)	22.0	28.0	36.0	34.8	38.2
Average		19.9	24.7	32.5	31.6	33.8
$\gamma = 90^{o}$ (Positive Step Temperature)						
h_{max}	(A)	20.4	26.8	32.8	62.0	52.8
	(B)	23.0	30.0	46.5	37.5	56.2
	(C)	24.4	28.0	46.4	43.0	64.0
Average		22.6	28.5	41.9	47.5	57.7
$\gamma = 105^{o}$ (Positive Step Temperature)						
h_{max}	(A)	17.4	20.8	28.2	23.5	25.7
	(B)	17.6	23.2	27.5	25.0	25.2
	(C)	16.8	23.0	27.0	23.5	23.0
Average		17.3	22.3	27.6	24.0	24.3
$\gamma = 135^{o}$ (Positive Step Temperature)						
h_{max}	(A)	8.0	39.0	16.2	16.7	18.9
	(B)	6.2	11.2	11.5	13.0	10.0
	(C)	8.8	13.7	16.2	13.2	17.6
Average		7.7	21.3	14.6	14.3	15.5

APPENDIX A

HEAT TRANSFER EXPERIMENTAL FILM COEFFICIENTS

This appendix contains the graphical presentation and tabular collection of the experimental heat transfer film coefficients reduced by computer and assembled in the research effort for contract NAS 8-5217.

The graphical displays for the complete body of data vary somewhat because the experimental accumulation required more than two years and the form of presentation was changed. The graphical display is presented on a scale, section view of the calorimeter, oriented to the free stream section. The abscissa is drawn along the calorimeter center-line; for some displays the origin is taken at the end of the calorimeter farthest from the free stream; for others the origin is taken at the intersection of the calorimeter center-line with the surface of the free stream flow through test section.

The average value of film coefficient (h_{avg}) is determined graphically by plotting all h values (for each series of elements) and fitting the best curve to the data. The maximum value of film coefficient (h_{max}) is determined be extrapolating the average experimental curve to the intersection of the calorimeter center-line with the surface of the free stream flow through test section.

No statistical method for obtaining the best fitting curve was used in obtaining h_{max} values. However, a quasi-statistical method is available that would probably reduce data scatter if it was applied.

APPENDIX A

Summary of Experimental Test Conditions

Diameter	Geometry	Velocity Range	Test	Table	Figures
4.00	$\gamma = 45^o$	100 - 300	Cold	A-I	A-1 - A-15
4.00	$\gamma = 75^o$	100 - 300	Cold	A-II	A-16 - A-30
4.00	$\gamma = 90^o$	100 - 300	Cold	A-III	A-31 - A-45
4.00	$\gamma = 105^o$	100 - 300	Cold	A-IV	A-46 - A-60
4.00	$\gamma = 135^o$	100 - 300	Cold	A-V	A-61 - A-75
4.00	$\gamma = 90^o$	200 - 300	Cold - Repeat	A-IX	A-43 - A-45
4.00	$\gamma = 75^o$	250	Cold - Repeat	A-VIII	A-76 - A-79
4.00	$\gamma = 90^o$	100 - 300	Hot	A-VII	A-95 - A-98
4.00	$\gamma = 75^o$	100 - 300	Hot	A-VI	A-80 - A-94
2.50	$\gamma = 45^o$	100 - 300	Hot	A-X	A-99 - A-103
2.50	$\gamma = 90^o$	100 - 300	Hot	A-XI	A-104 - A-108
2.50	$\gamma = 135^o$	100 - 300	Hot	A-XII	A-109 - A-112
1.25	$\gamma = 90^o$	100 - 300	High Temperature	A-XIII	A-113 - A-118
4.00	$\gamma = 75^o$	100 - 300	Cold versus Hot	A-II, A-VI	A-119 - A-123

TABLE A-I

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 45^{o}$, Positive Step Temperature)

Thermocouple Number	Velocity 100 fps Series A	B	C	Velocity 150 fps Series A	B	C	Velocity 200 fps Series A	B	C
1	-	-	-	-	-	-	-	-	-
2	1.857	4.517	1.794		3.548	-	0.918	1.691	1.160
3	2.717	3.856	0.753		2.660	-		1.558	0.680
4	-	2.475	-	-	4.379	-	-	1.622	-
5	2.158	3.704	1.451		1.486		1.367	0.300	1.887
6	2.262	-	0.198	1.715	-	0.835	0.903	-	1.076
7	2.509	4.760		0.336	1.354		0.534	1.956	2.126
8	-	1.859	1.719	0.722	0.288	1.499	1.623	1.822	0.839
9	-	-	-	-	-	-	-	-	-
10	2.183	-	2.495		-	-	1.401	-	2.889
11	1.819	6.173	1.794		3.264	1.537	1.933	3.724	3.176
12	-	6.789	-	-	3.569	-	-	3.240	-
13	-	-	-	-	-	-	-	-	-
14	4.390	11.681	5.564	2.115	4.286	1.594	4.952	6.902	5.410
15	5.096	10.897	6.152	10.726	4.176		5.545	5.723	6.484
16	7.272	-	7.854	15.030	-	1.652	8.721	-	10.118
17	5.994	15.533	4.726	15.965	19.837 9.395	2.628	7.592	2.461	10.175
18	-	23.409	-	-	9.299	-	-	10.093	-

TABLE A-I cont'd

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 45^{o}$, Positive Step Temperature)

Thermocouple Number	Velocity 250 fps Series			Velocity 300 fps Series		
	A	B	C	A	B	C
1	-	-	-	-	-	-
2				0.249		0.415
3	1.036				0.882	
4	-		-	-	0.229	-
5	0.781				0.983	0.744
6		-			-	
7	0.562	0.774	0.569	0.540	0.756	0.305
8	0.464	0.824			0.674	0.291
9	-	-	-	-	-	-
10	0.683	-	0.997	2.473	-	0.938
11	0.827	1.333	0.781	1.404	1.340	0.760
12	-	1.498	-	-	1.641	-
13	-	-	-	-	-	-
14	1.792	2.188	2.258	3.395	3.590	2.723
15	2.140	3.108	2.960	3.561	3.997	2.747
16	4.079	-	4.749	4.062	-	3.617
17	3.842	5.257	4.522	4.860	7.339	4.697
18	-	5.332	-	-	7.154	-

TABLE A-II

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT (γ = 75°, Positive Step Temperature)

Thermocouple Number	Velocity 100 fps Series			Velocity 150 fps Series			Velocity 200 fps Series		
	A	B	C	A	B	C	A	B	C
1	-	-	-	-	-	-	-	-	-
2	2.064	3.954	4.673	4.239	7.560	4.227	5.957	6.911	5.616
3	1.648	2.975	3.603	4.587	7.108	5.647	5.805	6.959	6.828
4	-	7.112	-	-	6.268 5.902	-	-	8.658	-
5	2.880	6.226	6.329	5.362 4.675	6.470 7.043	6.125 5.691	5.880	8.956	7.831
6	3.097	-		5.565 4.768	-	6.531 6.552	6.145	-	7.856
7	4.655	7.716	7.973	6.999	9.455	10.111	7.853	11.785	13.135
8	4.838	6.711	7.622	6.426	11.058	9.781	6.209	13.064	12.446
9	-	-	-	-	-	-	-	-	-
10	10.239	-	10.945	13.441	-	14.397	17.212	-	18.029
11	11.336	11.315	11.346	13.385	14.225	14.210	18.063	16.837	18.345
12	-	12.128	-	-	17.002	-	-	21.384	-
13	-	-	-	-	-	-	-	-	-
14	16.052	20.096	20.879	20.997	22.604	26.146	25.720	28.504	33.236
15	16.883	21.834	22.611	21.539	25.001	27.115	25.962	38.295	34.920
16	18.135	-	28.800	23.859	-	38.604	31.892	-	49.982
17	17.167	31.719	28.652	20.745	38.641	35.117		44.439	46.683
18	-	32.741	-	-	41.584	-	-	55.363	-

TABLE A-II cont'd

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT (γ = 75°, Positive Step Temperature)

Thermocouple Number	Velocity 250 fps Series A	Velocity 250 fps Series B	Velocity 250 fps Series C	Velocity 300 fps Series A	Velocity 300 fps Series B	Velocity 300 fps Series C
1	-	-	-	-	-	-
2	3.942	4.808	5.063	5.571	6.043	5.702
3	3.947	5.218	5.825	4.752	6.816	6.251
4	-	6.371	-	-	7.504	-
5	4.149	5.806	6.410	6.497	7.550	6.307
6	4.445	-	6.211	6.172	-	7.248
7	9.451	11.524	11.064	10.600	13.192	11.535
8	9.206	11.475	9.790	10.323	12.721	12.022
9	-	-	-	-	-	-
10	18.244	-	18.306	20.784	-	20.332
11	17.974	19.301	18.657	19.201	19.613	21.027
12	-	20.709	-	-	22.497	-
13	-	-	-	-	-	-
14	26.857	29.743	32.479	26.376	34.481	35.139
15	29.188	32.453	34.543	28.744	36.646	36.329
16	32.638	-	44.677	36.187	-	51.134
17	28.907	45.888	43.654	34.032	45.166	47.707
18	-	45.791	-	-	47.320	-

TABLE A-III

4 Inch Diameter Test Section

<u>HEAT</u> <u>TRANSFER</u> <u>FILM</u> <u>COEFFICIENT</u> ($\gamma = 90^{\circ}$, Positive Step Temperature)

Thermocouple Number	Velocity 100 fps Series			Velocity 150 fps Series			Velocity 200 fps Series		
	A	B	C	A	B	C	A	B	C
1	-	-	-	-	-	-	-	-	-
2	3.959		4.883	5.757	4.497	4.375		4.875	3.788
3	3.198	2.567	5.864	7.102	4.163	3.713	5.725	3.536	5.996
4	-	4.811	-	-	3.559	-	-	4.624	-
5.	5.464	5.552	4.010	4.669	5.606	7.247	8.840	11.145	6.697
6	4.702	-	8.132	4.555	-	4.544	10.073	-	5.808
7	5.460	5.551	10.053	9.047	9.300	7.763	8.252	9.954	11.798
8	4.655	4.698	10.236	10.554	8.671	6.530	9.889	11.906	13.302
9	-	-	-	-	-	-	-	-	-
10	10.855	-	13.708	19.323	-	14.708	17.218	-	25.875
11	12.365	10.402	16.889	18.919	16.602	15.597	14.643	23.555	23.280 23.952
12	-	11.565	-	-	17.942	-	-	23.155	-
13	-	-	-	-	-	-	-	-	-
14	19.731	21.028	21.199	23.303	27.347	26.416	30.389	43.514	44.140
15	19.463	21.903 17.002	24.565	26.633	27.762	27.927	31.387	46.307	45.731
16	25.217	-	29.147	32.043	-	33.839	40.524	-	57.113
17	23.428	32.065	29.264	28.022	38.595	35.122	45.912	53.354	54.591
18	-	33.897	-	-	47.709	-	-	70.114	-

TABLE A-III cont'd

4 Inch Diameter Test Section

<u>HEAT</u> <u>TRANSFER</u> <u>FILM</u> <u>COEFFICIENT</u> (γ = 90^{o}, Positive Step Temperature)

Thermocouple Number	Velocity 250 fps Series			Velocity 300 fps Series		
	A	B	C	A	B	C
1	-	-	-	-	-	-
2	4.834	4.254	9.348	16.764	5.696	3.278
3	4.326	4.767	6.406	5.308	4.065	3.907
4	-	7.960	-	-	7.880	-
5	9.082	6.255	10.561	7.799	7.333	7.991
6	10.594	-	10.704	10.311	-	11.462
7	15.838	12.500	16.149	19.268	22.243	18.601
8	12.205	9.809	16.788	23.590	19.548	21.864
9	-	-	-	-	-	-
10	34.866	-	25.778	36.622	-	47.127
11	36.744	24.560	25.604	40.768	33.776	45.725
12	-	27.741	-	-	30.651	-
13	-	-	-	-	-	-
14	59.804	40.576		56.402	49.729	48.907
15	65.459	40.251	34.764	44.988	56.910	55.618
16	74.919	-	66.704	63.560	-	75.119
17	73.523	45.699	52.178	55.906	88.792	79.999
18	-	52.283	-	-	78.293	-

TABLE A-IV

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT (γ = 105°, Positive Step Temperature)

Thermocouple Number	Velocity 100 fps Series A	B	C	Velocity 150 fps Series A	B	C	Velocity 200 fps Series A	B	C
1	-	-	-	-	-	-	-	-	-
2	4.417	6.759	0.310	4.663	3.478	3.152	4.843	1.027	1.992
3	3.552	4.361	1.173	4.436	3.781	1.960	1.200	4.888	5.417
4	-	3.273	-	-	9.090	-	-	8.843	-
5	6.593	4.350	2.237	4.812	8.593	3.098	3.826	8.352	7.600
6	6.586	-	2.326	6.370	-	4.469	4.130	-	5.451
7	7.007 6.412	8.432	4.508	8.375	11.431	6.294	8.236	10.558	7.156
8	7.407	1.091	8.776	7.304	10.663	7.592	9.529	10.825	5.241
9	-	-	-	-	-	-	-	-	-
10	10.861 8.996	-	3.592	13.894	-	9.326 11.221	19.554	-	13.894
11	12.782	7.693	8.713	14.639	13.506	9.792	16.894	17.449	13.737
12	-	12.052	-	-	15.316	-	-	19.633	-
13	-	-	-	-	-	-	-	-	-
14	18.045	19.671	18.174	21.512	25.871	27.555	29.939	30.356	
15	20.053	18.517	17.884	21.592	25.935	26.672	28.419	32.188	33.878 35.424
16	21.023	-	24.228	28.446	-	35.328	32.839	-	44.290 32.905
17	19.255	24.960	27.755	25.797	33.269	37.116	40.769	37.695	55.957 35.682
18	-	25.511	-	-	38.232	-	-	36.214	-

TABLE A-IV cont'd

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT (γ = 105^{o}, Positive Step Temperature)

Thermocouple Number	Velocity 250 fps Series			Velocity 300 fps Series		
	A	B	C	A	B	C
1	-	-	-	-	-	-
2	4.839	3.305	4.628	5.020	3.602	10.905
3	5.867	5.838	2.571	6.297	5.370	5.614
4	-	4.695	-	-	2.892	-
5	4.972	4.633	2.498	5.316	6.497	3.125
6	3.802	-	2.574	6.867	-	2.511
7	5.935	9.975	4.837	8.602	8.110	6.200
8	8.825	10.372	5.484	8.832	11.325	6.004
9	-	-	-	-	-	-
10	13.826	-	9.147	14.520	-	9.957
11	14.106	13.763	11.933	14.464	16.582	10.650
12	-	17.512	-	-	16.183	-
13	-	-	-	-	-	-
14	25.983	25.048	25.237	27.609	25.975	23.693
15	26.103	29.847	23.109	26.464	26.461	22.860
16	32.565	-	37.320	39.346	-	35.319
17	33.430	31.102	36.020	34.151	34.160	37.945
18	-	39.622	-	-	41.829	-

TABLE A-V

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 135^o$, Positive Step Temperature)

Thermocouple Number	Velocity 100 fps Series A	B	C	Velocity 150 fps Series A	B	C	Velocity 200 fps Series A	B	C
1	-	-	-	-	-	-	-	-	-
2	0.998		2.005	3.264	0.787	2.234	1.584		0.405
3			3.346	3.778	2.632	2.528	1.740	0.926	1.886
4	-	0.075	-	-	1.185	-	-	0.455	-
5	3.552	2.157		1.448	1.424	2.106	3.589	0.586	1.788
6	2.995	-		11.237	-	1.290	2.837	-	2.199
7		0.019	0.837	9.859	2.122	1.305	0.905	1.250	1.337
8	1.182	1.949	1.444	11.709	2.154	4.221	2.609	1.384	3.297
9	-	-	-	-	-	-	-	-	-
10	3.689	-	1.915	23.957	-	4.274	3.862	-	4.337
11	2.774	1.723	2.632	15.706	3.865	3.703	4.500	3.340	7.247
12	-	0.310	-	-	5.400	-	-	4.020	-
13	-	-	-	-	-	-	-	-	-
14	4.539	5.333	4.148	44.567	7.772	7.999	10.328	6.914	8.526
15	6.982	5.795	5.786	48.859	10.123	8.594	9.718	6.671	10.597
16	1.694	-	9.193	20.019	-	16.439	17.776	-	20.268
17	25.439	9.903	10.805	22.585	14.514	15.399	19.909	14.728	17.806
18	-	10.918	-	-	12.434	-	-	15.499	-

TABLE A-V cont'd

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 135^{\circ}$, Positive Step Temperature)

Thermocouple Number	Velocity 250 fps Series A	B	C	Velocity 300 fps Series A	B	C
1	-	-	-	-	-	-
2	3.346	0.476	3.874	4.209	3.225	2.078
3	2.866		2.370	4.260	1.400	1.803
4	-	0.902	-	-	1.196	-
5	2.661		4.029	2.854		3.206
6	2.873	-	4.121	2.264	-	2.778
7	4.040	2.497	1.886	2.330	4.407	3.574
8	3.372	2.715	6.034	4.378	1.798	6.507
9	-	-	-	-	-	-
10	6.764	-	8.741	6.206	-	9.395
11	5.289	3.080	3.375	6.550	3.937	7.060
12	-	4.526	-	-	4.849	-
13	-	-	-	-	-	-
14	10.599	8.747	9.869	17.531	9.430	14.313
15	15.757	10.241	9.738	6.909	6.885	13.734
16	18.673	-	20.680	19.638	-	24.313
17	16.885	17.292	21.798	22.038	9.576	4.805
18	-	13.796	-	-	12.529	-

TABLE A-VI

4 Inch Diameter Test Section

<u>HEAT TRANSFER FILM COEFFICIENT</u> ($\gamma = 135^{\circ}$, Negative Step Temperature)

Thermocouple Number	Velocity 100 fps Series A	B	C	Velocity 150 fps Series A	B	C	Velocity 200 fps Series A	B	C
1	-	-	-	-	-	-	-	-	-
2	3.416	3.281	3.545	4.209	3.149	4.810		3.474	4.893
3	3.393	3.483	3.445	4.431		4.909	4.226	3.340	4.721
4	-	3.451	-	-	2.499	-	-	3.853	-
5	3.727	4.546	4.402	2.733	3.244	3.481	4.458	4.345	4.649
6	3.693	-	4.115	3.197	-	3.521	4.712	-	4.729
7	3.823	2.961	3.738	4.707	3.945	5.214	6.639	5.546	7.191
8	3.463	3.225	5.834	4.586	4.191	4.677	6.391	5.540	7.235
9	-	-	-	-	-	-	-	-	-
10	4.750	-	5.796	7.102	-	7.782	8.116	-	8.071
11	5.079	3.810	6.061	6.352	5.902	7.251	8.040	7.551	8.023
12	-	4.687	-	-	6.781	-	-	7.557	-
13	-	-	-	-	-	-	-	-	-
14	5.440	5.028	7.501	7.706	6.827	9.663	11.929	10.132	13.915
15	5.777	5.259	7.370	8.210	7.581	9.596	12.150	11.428	14.541
16	6.398	-	9.252	7.759	-	11.787	13.283	-	19.971
17	5.748	7.178	9.051	7.601	9.301	11.404	12.931	14.996	18.169
18	-	7.327	-	-	10.520	-	-	16.548	-

TABLE A-VI cont'd

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 135^{o}$, Negative Step Temperature)

Thermocouple Number	Velocity 250 fps Series A	B	C	Velocity 300 fps Series A	B	C
1	-	-	-	-	-	-
2	4.893	3.292	4.758	6.100	4.612	5.167
3	4.700	3.792	4.756	5.456	4.074	5.856
4	-	3.672	-	-	5.024	-
5	5.620	6.861	4.185	6.706	7.669	5.442
6	5.620	-	6.346	6.966	-	6.566
7	5.717	5.354	5.782	7.537	6.622	7.938
8	5.339	5.452	6.171	6.872	6.494	8.289
9	-	-	-	-	-	-
10	9.582	-	9.785	10.056	-	10.084
11	9.138	8.064	9.653	10.502	10.011	10.088
12	-	9.479	-	-	10.945	-
13	-	-	-	-	-	-
14	12.257	11.528	14.960	16.421	14.405	19.426
15	13.049	15.895	15.510	16.224	16.291	19.416
16	12.485	-	21.702	18.251	-	26.051
17	13.599	16.136	19.475	16.488	18.814	24.121
18	-	19.390	-	-	20.206	-

TABLE A-VII

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 90^o$, Negative Step Temperature)

Thermocouple Number	Velocity 100 fps Series A	B	C	Velocity 150 fps Series A	B	C	Velocity 200 fps Series A	B	C
1	-	-	-	-	-	-	-	-	-
2	3.682	3.862	3.591	4.380	3.869	4.139	4.416	4.634	4.642
3	3.394	4.261	2.622	4.032	4.848	3.271	4.009	4.494	4.487
4	-	3.430	-	-	3.780	-	-	4.748	-
5	3.128	2.817	2.534	3.446	3.530	3.411	4.732	5.732	4.781
6	2.995	-	2.666	3.112	-	3.373	5.128	-	4.155
7	2.692	3.729	3.730	3.952	4.247	4.150	5.786	6.988	5.799
8	3.246	3.912	3.104	4.034	4.468	4.562	5.440	6.420	5.650
9	-	-	-	-	-	-	-	-	-
10	5.306	-	4.906	6.012	-	5.941	8.008	-	6.743
11	6.193	4.196		6.573	6.199	5.360	7.894	8.124	7.259
12	-	4.601	-	-	6.144	-	-	9.847	-
13	-	-	-	-	-	-	-	-	-
14	4.467	5.538	6.224	6.766	7.390	7.732	11.145	11.427	11.106
15	5.336	4.945	5.511	6.268	8.429	7.741	11.505	10.749	11.945
16	16.557	-	24.574	6.111	-	9.249	8.310	-	15.171
17	16.524	24.327	22.772	5.041	9.122	7.940	10.182	13.403	14.237
18	-	22.175	-	-	9.928	-	-	15.495	-

TABLE A-VII cont'd

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT (γ = 90°, Negative Step Temperature)

Thermocouple Number	Velocity 250 fps Series			Velocity 300 fps Series		
	A	B	C	A	B	C
1	-	-	-	-	-	-
2	3.299	3.050	3.800	4.006	4.523	4.107
3	3.899	5.137	4.641	5.867	4.932	5.185
4	-	4.819	-	-	7.066	-
5	5.176	5.947	5.814	6.157	6.451	7.372
6	4.915	-	4.618	6.558	-	6.274
7	6.079	5.764	6.039	7.091	8.180	7.557
8	7.038	6.855	5.236	7.309	8.588	8.057
9	-	-	-	-	-	-
10	8.792	-	8.049	8.618	-	8.848
11	8.565	8.779	9.025	10.064	9.936	9.197
12	-	9.722	-	-	11.884	-
13	-	-	-	-	-	-
14	14.200	14.433	14.925	15.632	14.841	15.953
15	13.878	15.082	14.393	16.104	22.724	16.225
16	15.945	-	19.741	16.636	-	22.876
17	12.970	18.962	19.373	15.641	21.022	22.155
18	-	23.307	-	-	25.235	-

TABLE A-VIII

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT (γ = 75°. Positive Step Temperature) Repeat Run

Thermocouple Number	Velocity 250 fps Series A	B	C
1	-	-	-
2	5.650	5.733	6.804
3	5.428	6.254	7.434
4	-	5.596	-
5	6.353	6.405	6.628
6	7.260	-	6.890
7	7.561	8.762	9.328
8	8.577	10.247	
9	-	-	-
10	14.581	-	14.762
11	24.519	15.570	15.324
12	-	16.572	-
13	-	-	-
14	21.878	22.934	24.991
15	22.591	27.570	26.133
16	28.076	-	38.187
17	24.682	36.178	36.119
18	-	39.875	-

TABLE A-IX

4 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 90^{\circ}$, Positive Step Temperature) Repeat Runs

Thermocouple Number	Velocity 200 fps Series A	Velocity 200 fps Series B	Velocity 200 fps Series C	Velocity 300 fps Series A	Velocity 300 fps Series B	Velocity 300 fps Series C
1						
2	1.001	4.506	4.166	4.067	3.821	3.640
3	1.829	4.781	5.629	3.617	4.019	3.996
4		4.021			6.586	
5	4.304	5.506	3.948	5.732	6.211	8.032
6	4.071		4.140	5.917		6.058
7	10.183	9.854	9.252	6.423	7.581	7.095
8	9.919	10.537	9.109	6.366	7.966	6.741
9						
10	16.266		15.499	10.356		11.842
11	16.221	16.355	16.766	11.554	10.981	11.038
12		17.701			11.761	
13						
14	28.783	26.305	29.055	16.029	16.858	19.293
15	28.924	28.102	31.506	15.960	19.506	18.875
16	36.995		45.922	25.842		36.132
17	32.794	43.709	47.557	22.041	30.670	32.780
18		43.874			33.538	

TABLE A-X

2.5 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 45^{o}$, Negative Step Temperature)

Thermocouple Number	Velocity 100 fps Series			Velocity 150 fps Series			Velocity 200 fps Series		
	A	B	C	A	B	C	A	B	C
1	-	-	-	-	-	-	-	-	-
2	1.726	1.888	0.854	1.517	1.248	1.098	1.959	2.410	1.673
3	1.616	2.095	1.422	1.174	1.529	1.093	2.307	2.074	1.674
4	-	1.693	-	-	1.239	-	-	2.235	-
5	1.793	1.894	1.399	1.070	1.064	0.957	2.513	1.983	1.770
6	1.799	-	1.506	1.152	-	1.130	2.052	-	1.603
7	1.715	2.315	1.374	1.596	1.399	1.376	2.291	2.694	2.451
8	1.244	2.071	1.661	1.829	1.461	0.965	2.444	3.096	2.105
9	-	-	-	-	-	-	-	-	-
10	3.062	-	2.868	2.744	-	3.428	3.484	-	3.722
11	2.839	3.927	2.689	3.148	2.886	3.128	3.714	4.574	3.622
12	-	2.501	-	-	2.483	-	-	4.155	-
13	-	-	-	-	-	-	-	-	-
14	6.113	6.785	6.020	6.428	6.290	5.981	7.523	7.990	7.704
15	6.254	6.833	6.355	6.231	5.808	6.431	7.451	8.566	7.734
16	9.747	-	8.358	9.484	-	8.920	11.982	-	11.199
17	9.376	9.688	9.196	9.644	11.603	8.812	12.372	11.358	8.846
18	-	9.394	-	-	11.053	-	-	12.842	-

TABLE A-X cont'd

2.5 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT (γ = 45^{o}, Negative Step Temperature)

Thermocouple Number	Velocity 250 fps Series			Velocity 300 fps Series		
	A	B	C	A	B	C
1	-	-	-	-	-	-
2	1.621	1.532	1.963	0.832	0.947	0.431
3	1.889	1.507	1.693	0.499	1.324	0.431
4	-	2.010	-	-	2.018	-
5	1.770	1.324	1.559	2.777	2.234	2.342
6	1.833	-	1.626	2.336	-	2.323
7	2.228	2.373	1.814	2.134	3.313	2.244
8	2.386	2.578	2.308	2.387	3.675	2.495
9	-	-	-	-	-	-
10	4.808	-	4.535	2.410	-	4.711
11	4.610	4.751	4.253	3.041	5.123	4.248
12	-	4.479	-	-	2.932	-
13	-	-	-	-	-	-
14	8.113	8.366	8.158	6.936	8.022	8.130
15	8.002	8.268	7.779	8.206	8.887	7.452
16	14.503	-	11.397	15.218	-	14.466
17	14.862	15.562	8.551	15.038	17.974	10.083
18	-	14.816	-	-	16.262	-

TABLE A-XI

2.5 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT (γ = 90°. Negative Step Temperature)

Thermocouple Number	Velocity 100 fps Series			Velocity 150 fps Series			Velocity 200 Series		
	A	B	C	A	B	C	A	B	C
1	-	-	-	-	-	-	-	-	-
2	0.725	1.086	1.592			0.688	0.275		1.024
3	0.460	0.000	1.086	2.846	0.000		2.858		
4	-	0.689	-	-	1.520	-	-	3.105	-
5	1.117	0.594	1.148	0.644	1.015	1.231	0.000	2.312	1.800
6	0.905	-	1.224	2.116	-	1.619	2.409	-	1.705
7	2.722	2.536	3.805	3.626	2.719	1.547	0.602	6.390	6.541
8	2.992	2.586	3.668	2.704	3.124	2.130	5.613	5.429	5.662
9	-	-	-	-	-	-	-	-	-
10	5.074	-	4.279	3.788	-	4.470	7.047	-	5.994
11	1.936		4.449	5.532	4.220	5.404	6.535	7.390	7.506
12	-	5.507	-	-	5.205	-	-	7.989	-
13	-	-	-	-	-	-	-	-	-
14	6.732	4.634	6.162	7.642	10.028	9.454	10.499	10.709	9.811
15	5.959	4.235	4.197	6.525	6.634	6.862	10.400	9.985	10.739
16	7.084	-	4.550	6.316	-	6.131	12.709	-	12.639
17	6.399	9.119	6.100	7.987	4.369	4.223	8.539	16.086	5.693
18	-	5.611	-	-	7.129	-	-	11.916	-

TABLE A-XI cont'd

2.5 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 90^{o}$, Negative Step Temperature)

Thermocouple Number	Velocity 250 fps Series			Velocity 300 fps Series		
	A	B	C	A	B	C
1	-	-	-	-	-	-
2		0.000		0.939	0.599	1.848
3	0.000		0.261	1.592	1.818	1.767
4	-	1.749	-	-	1.873	-
5	1.135	1.949	0.924	0.283	2.029	1.476
6	1.938	-	0.912	2.974	-	2.060
7	3.507	4.715	3.396	5.405	4.994	6.031
8	4.502	4.165	4.691	5.656	5.129	5.123
9	-	-	-	-	-	-
10	12.950	-	6.593	7.805	-	7.036
11	5.714	6.770	7.216	7.123	7.058	7.737
12	-	5.542	-	-	8.475	-
13	-	-	-	-	-	-
14	10.213	9.228	6.117	12.397	12.448	11.702
15	9.347	8.050	8.461	12.411	11.012	11.122
16	12.509	-	13.386	15.840	-	14.999
17	5.140	17.204	10.507	12.413	15.034	13.442
18	-	15.260	-	-	14.766	-

TABLE A-XII

2.5 Inch Diameter Test Section

HEAT TRANSFER FILM COEFFICIENT ($\gamma = 135^{o}$, Negative Step Temperature)

Thermocouple Number	Velocity 100 fps Series			Velocity 150 fps Series			Velocity 200 fps Series		
	A	B	C	A	B	C	A	B	C
1	-	-	-	-	-	-	-	-	-
2	1.603	1.508	0.609	1.731	1.306	1.259	0.739	0.524	1.400
3	1.032	0.467	0.879	2.252	1.298	2.081	0.519	0.571	0.599
4	-	1.211	-	-	1.658	-	-	1.730	-
5	1.059	1.047	0.975	1.357	1.665	1.842	1.453	1.908	0.411
6	1.201	-	1.205	0.911	-	0.744		-	2.030
7	1.439	1.077	1.341	1.897	1.411	2.177	1.422	2.458	2.183
8	1.192	1.384	1.192	1.954	2.312	1.977	1.477	2.093	1.759
9	-	-	-	-	-	-	-	-	-
10	2.126	-	2.079	2.117	-	2.807	2.898	-	2.172
11	1.724	2.386	1.889	1.786	1.344	1.951	3.383	2.613	2.452
12	-	2.502	-	-	2.480	-	-	2.565	-
13	-	-	-	-	-	-	-	-	-
14	3.368	2.510	2.970	3.373	3.047	2.650	3.936	4.362	3.922
15	3.124	3.009	3.227	3.075	2.556	2.937	4.394	4.004	4.671
16	4.825	-	5.163	4.014	-	5.479	5.405	-	5.545
17	5.275	5.050	4.585	4.721	4.957	5.013	5.008	5.696	6.284
18	-	5.313	-	-	4.649	-	-	5.772	-

TABLE A-XII cont'd

2.5 Inch Diameter Test Section

<u>HEAT</u> <u>TRANSFER</u> <u>FILM</u> <u>COEFFICIENT</u> (γ = 135^o, Negative Step Temperature)

Thermocouple Number	Velocity 250 fps Series			Velocity 300 fps Series		
	A	B	C	A	B	C
1	-	-	-	-	-	-
2	1.552	1.093	1.260	1.452	2.351	1.852
3	1.210	1.011	1.263	2.342	2.798	2.241
4	-	1.353	-	-	1.815	-
5	1.840	1.215	13.609	1.838	0.922	1.551
6	2.213	-	1.284	1.246	-	0.499
7	2.002	1.825	1.605	2.062	2.981	2.642
8	1.802	0.872	2.171	2.832	1.909	2.672
9	-	-	-	-	-	-
10	2.825	-	2.140	3.303	-	2.826
11	1.458	2.584	2.292	2.064	1.896	2.362
12	-	1.684	-	-	2.216	-
13	-	-	-	-	-	-
14	3.622	4.006	3.573	4.521	4.561	4.108
15	4.074	4.173	4.807	4.521	4.325	4.149
16	6.979	-	6.349	7.785	-	6.507
17	6.884	6.934	6.913	7.713	7.566	7.802
18	-	7.117	-	-	7.638	-

TABLE A-XIII

1.25 Inch Diameter Test Section

<u>HEAT</u> <u>TRANSFER</u> <u>FILM</u> <u>COEFFICIENT</u> (γ = 90, Positive Step Temperature)

High Temperature Test Data

Thermocouple Number	V = 170 fps, T = 506 °F Series A	B	C	V = 172 fps, T = 429 °F Series A	B	C	V = 212 fps, T = 401 °F Series A	B	C
1	-	-	-	-	-	-	-	-	-
2	0.821	0.680	0.435	2.054	3.375	3.424	1.845	1.779	1.883
3	0.500	0.921	0.792	2.951	3.414	2.969	1.858	1.730	1.862
4	-	1.686	-	-	3.909	-	-	2.105	-
5	1.002	1.163	0.722	4.883	4.180	4.316	2.802	2.078	2.151
6	0.515	-	1.374	4.892	-	4.924	2.078	-	2.096
7	0.982	0.828	1.224	2.143	2.817	2.791	3.263	3.577	2.823
8	1.096	1.091	1.274	2.555	2.791	2.818	3.967	2.534	3.474
9	-	-	-	-	-	-	-	-	-
10	7.045	-	6.502	6.083	-	6.304	5.943	-	4.069
11	7.144	8.360	6.653	5.485	6.644	5.596	4.274	3.673	3.294
12	-	7.542	-	-	6.027	-	-	4.073	-
13	-	-	-	-	-	-	-	-	-
14	12.596	12.537	9.951	10.366	8.550	7.146	14.867	12.828	14.974
15	11.935	12.881	10.959	8.843	9.394	9.205	14.609	10.431	14.173
16	10.938	-		11.029	-	12.242	16.533	-	16.336
17	11.933	14.491	12.973	10.113	11.847	11.056	15.100	16.597	14.156
18	-	13.694	-	-	10.812	-	-	15.706	-

TABLE A-XIII cont'd

1.25 Inch Diameter Test Section

<u>HEAT TRANSFER FILM COEFFICIENT</u> (γ = 90, Positive Step Temperature)

High Temperature Test Data

Thermocouple Number	V = 208 fps, T = 302^{o}F Series			V = 244 fps, T = 300^{o}F Series			V = 292 fps, T = 397^{o}F Series		
	A	B	C	A	B	C	A	B	C
1	-	-	-	-	-	-	-	-	-
2	1.246	1.607	1.330	3.300	3.630	3.030	1.696	2.217	1.243
3	1.615	1.607	1.607	3.300	3.397	3.030	2.498	2.205	4.631
4	-	1.601	-	-	4.693	-	-		-
5	1.611	1.601	1.611	3.988	3.901	4.278			
6	1.580	-	1.632	5.248	-	3.844		-	
7	2.537	2.532	2.174	5.855	5.610	5.259	5.486	5.144	4.354
8	3.037	2.527	3.448	6.113	4.953	5.442	5.623	4.451	2.232
9	-	-	-	-	-	-	-	-	-
10	6.348	-	6.022	11.174	-	10.684	6.117	-	7.073
11	6.627	6.458	6.178	11.426	10.708	11.985	6.578	9.025	8.209
12	-	6.112	-	-	10.691	-	-	8.135	-
13	-	-	-	-	-	-	-	-	-
14	13.776	14.059	13.364	17.078	16.271	14.898	5.694	5.783	3.745
15	13.482	14.010	13.635	16.326	17.844	15.662	5.822	9.234	8.500
16	13.955	-	15.855	15.973	-	17.087		-	
17	12.223	14.020	15.416	14.609	18.905	16.103			
18	-	14.910	-	-	18.624	-	-		-

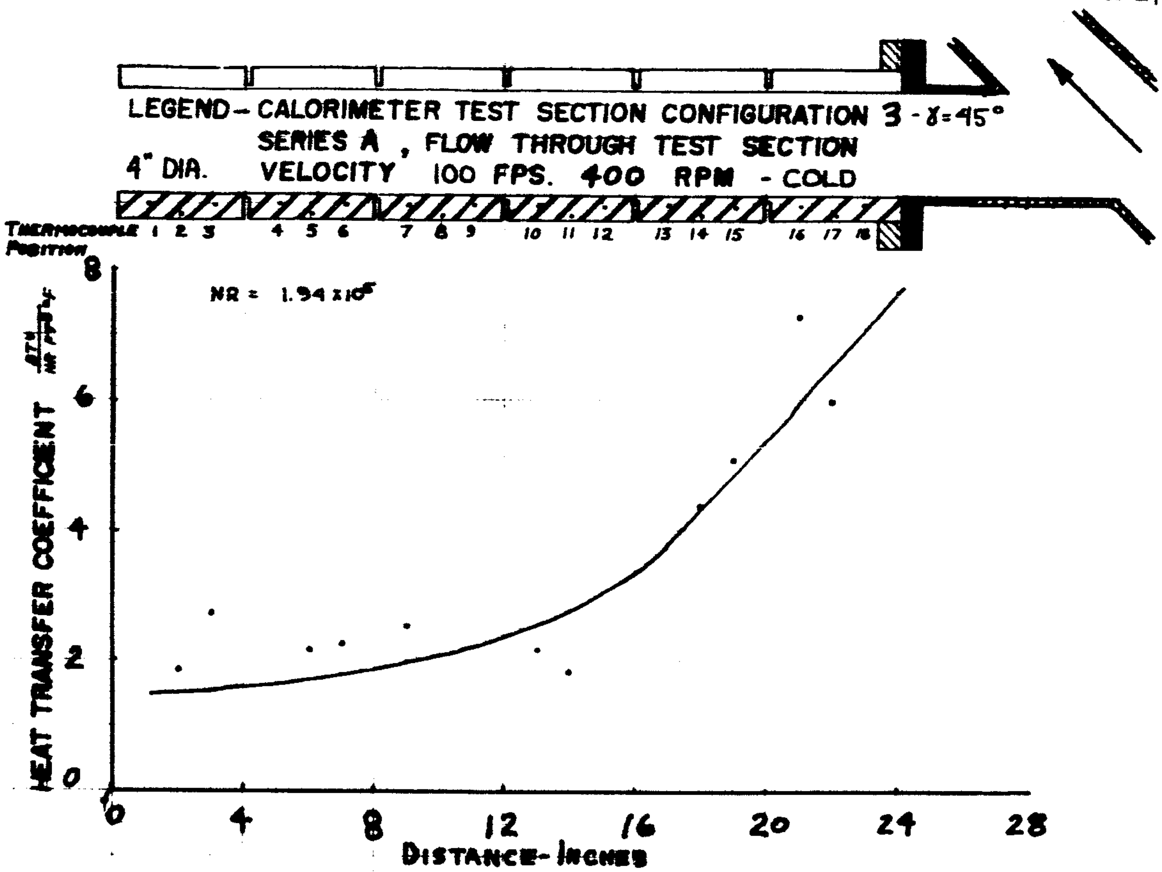


FIGURE A-1

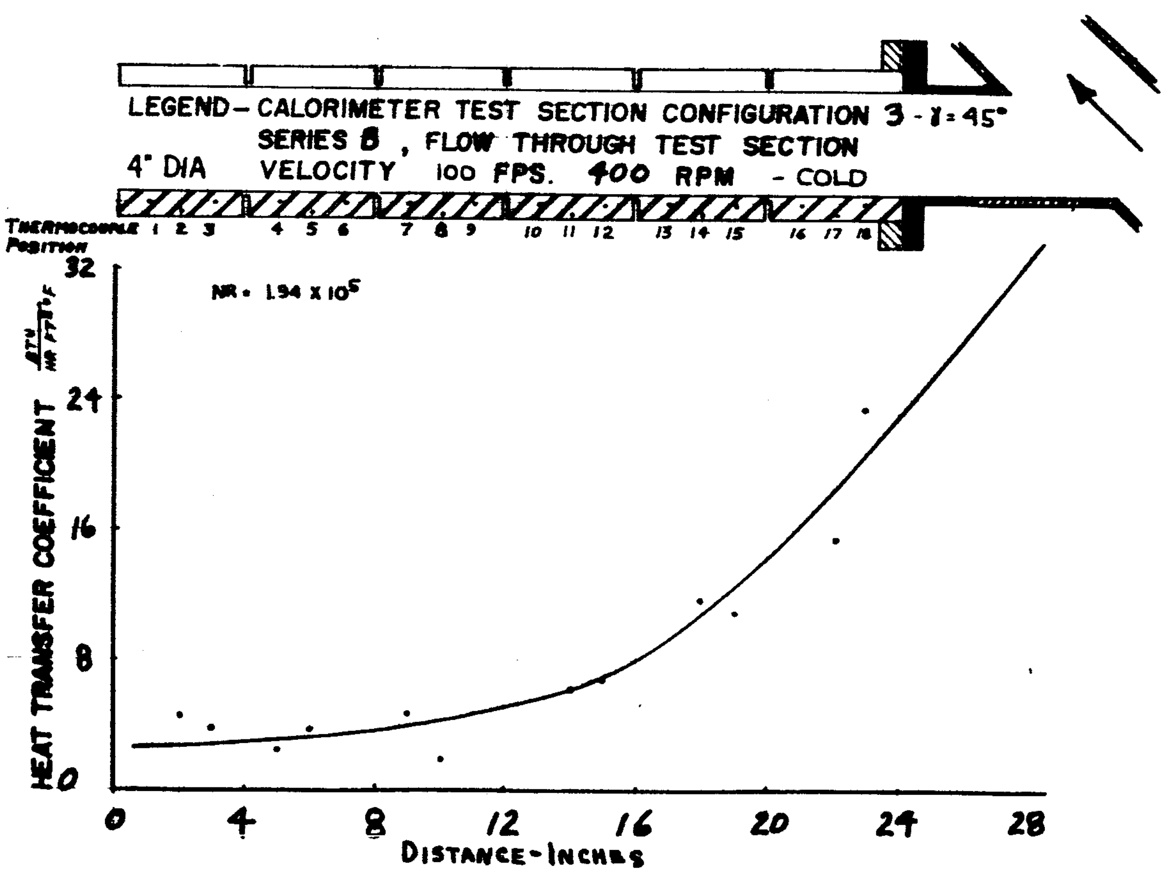


FIGURE A-2

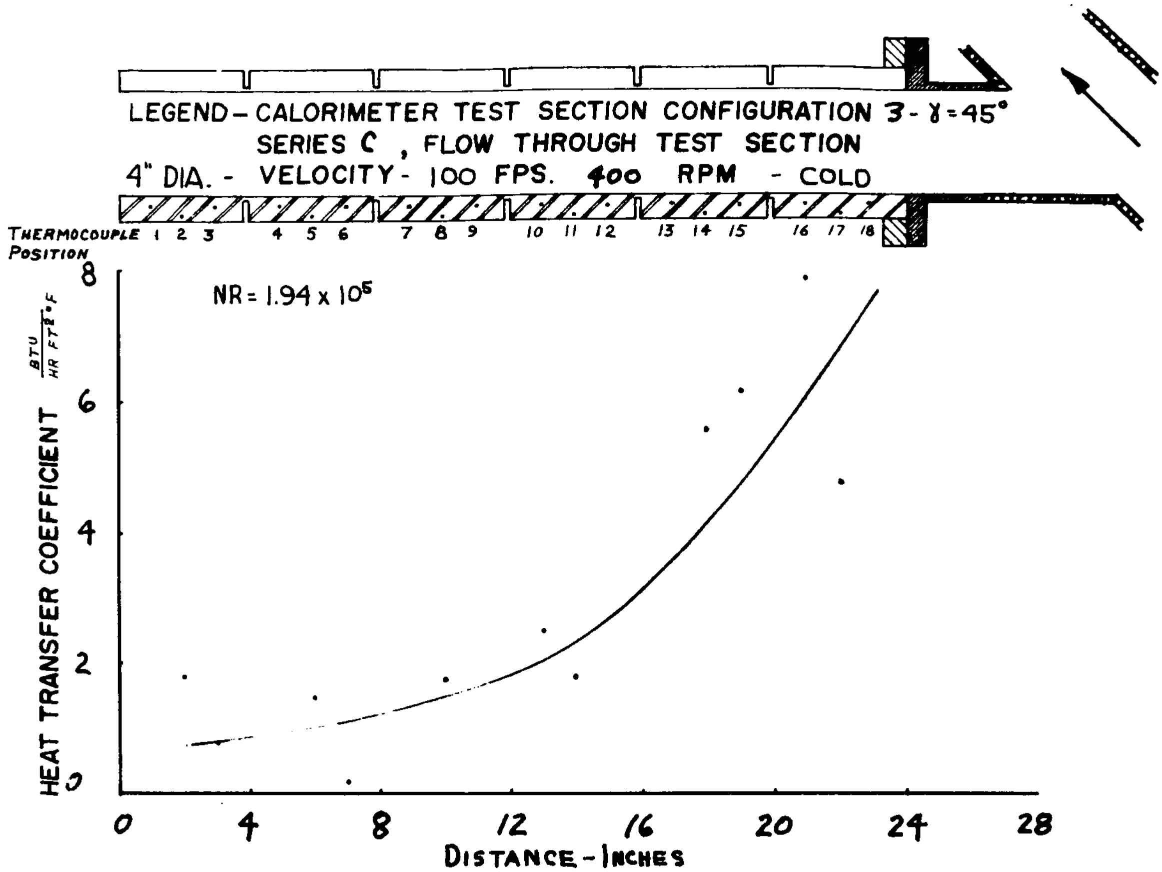


FIGURE A-3

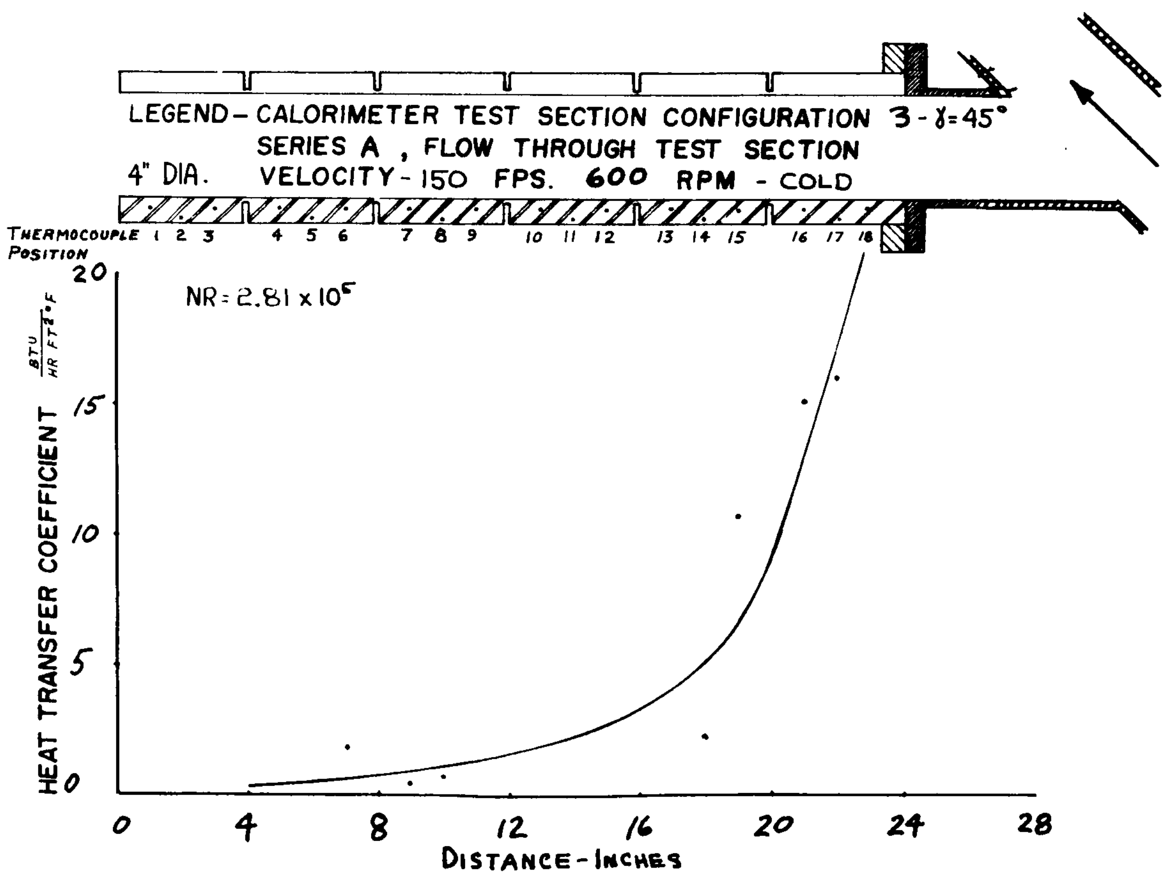


FIGURE A-4

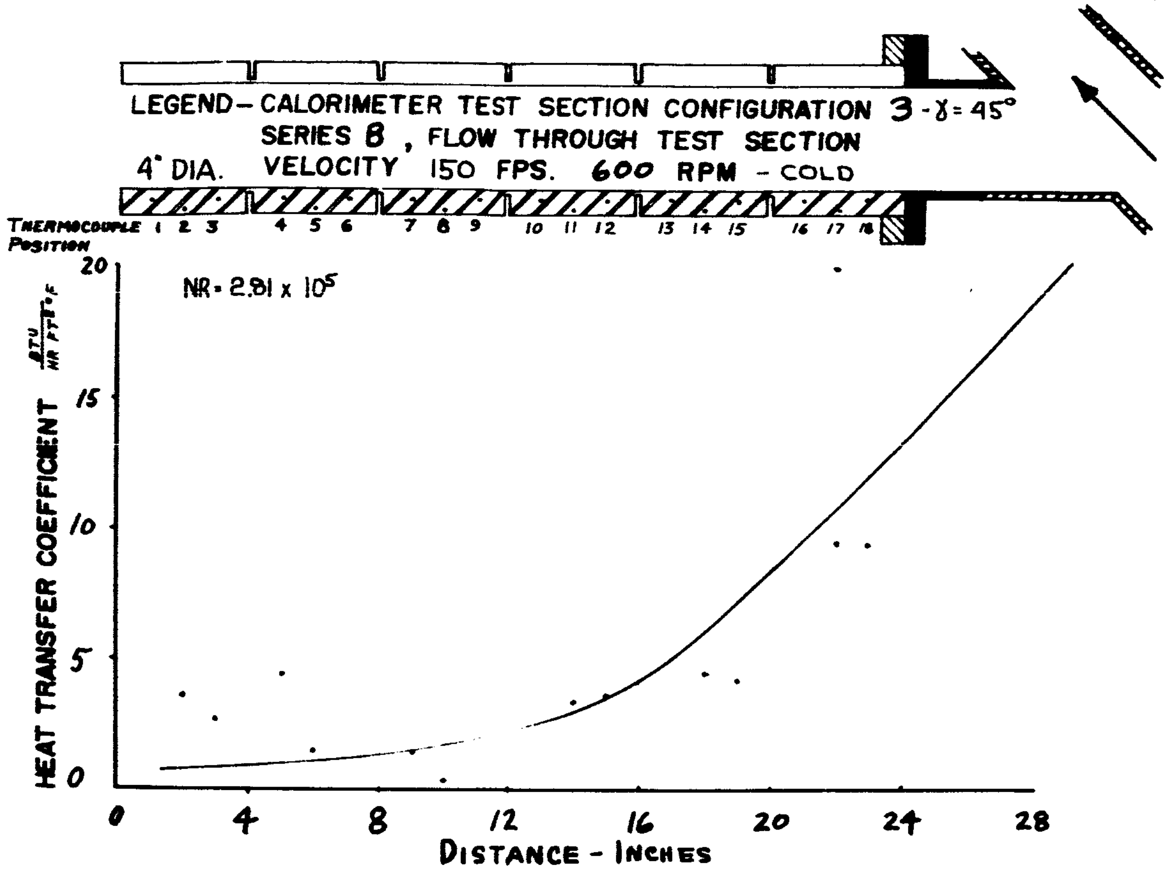


FIGURE A-5

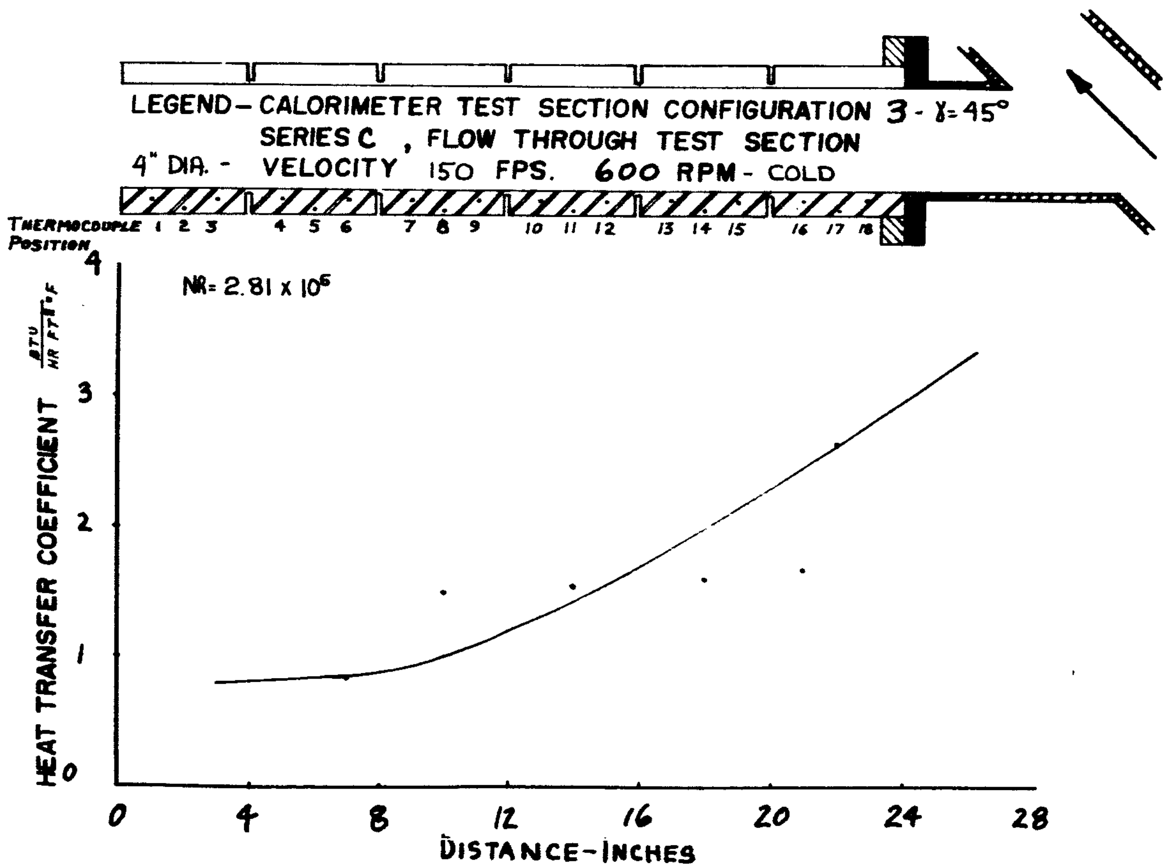


FIGURE A-6

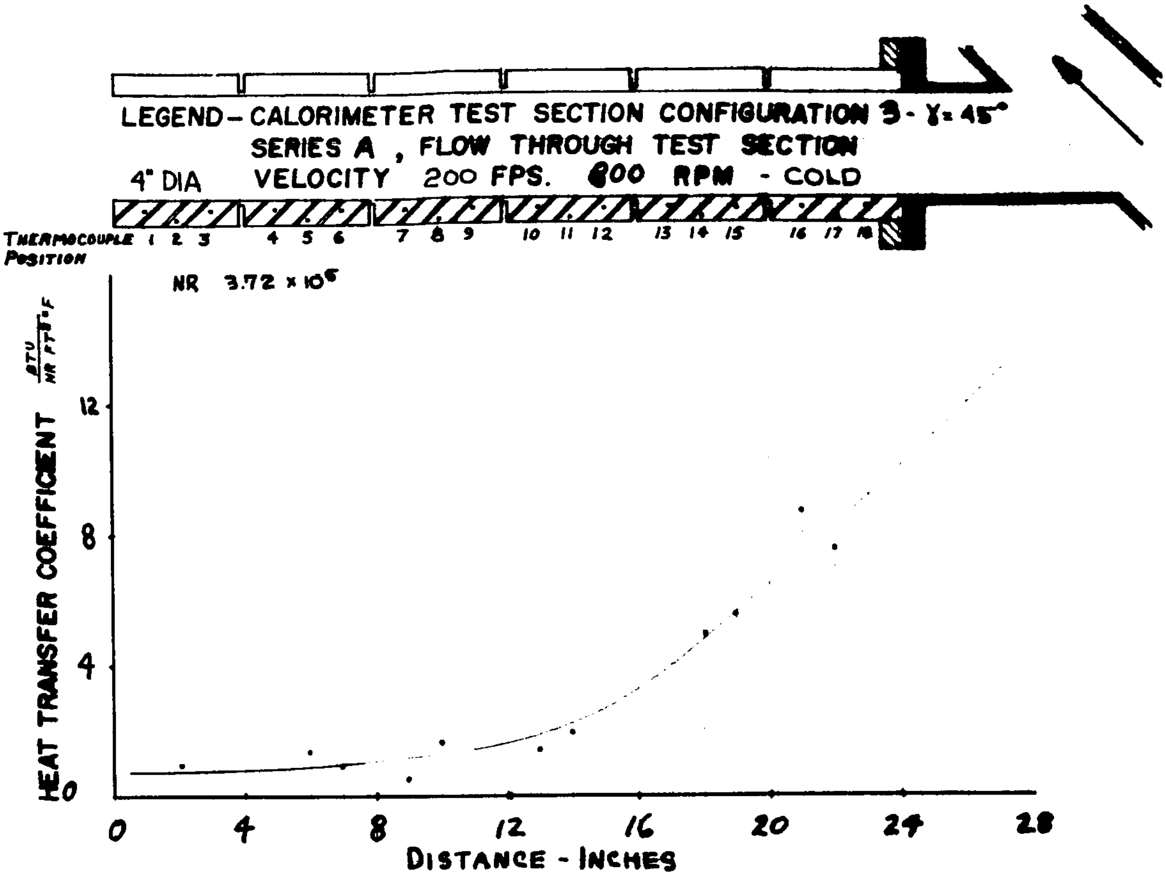


FIGURE A-7

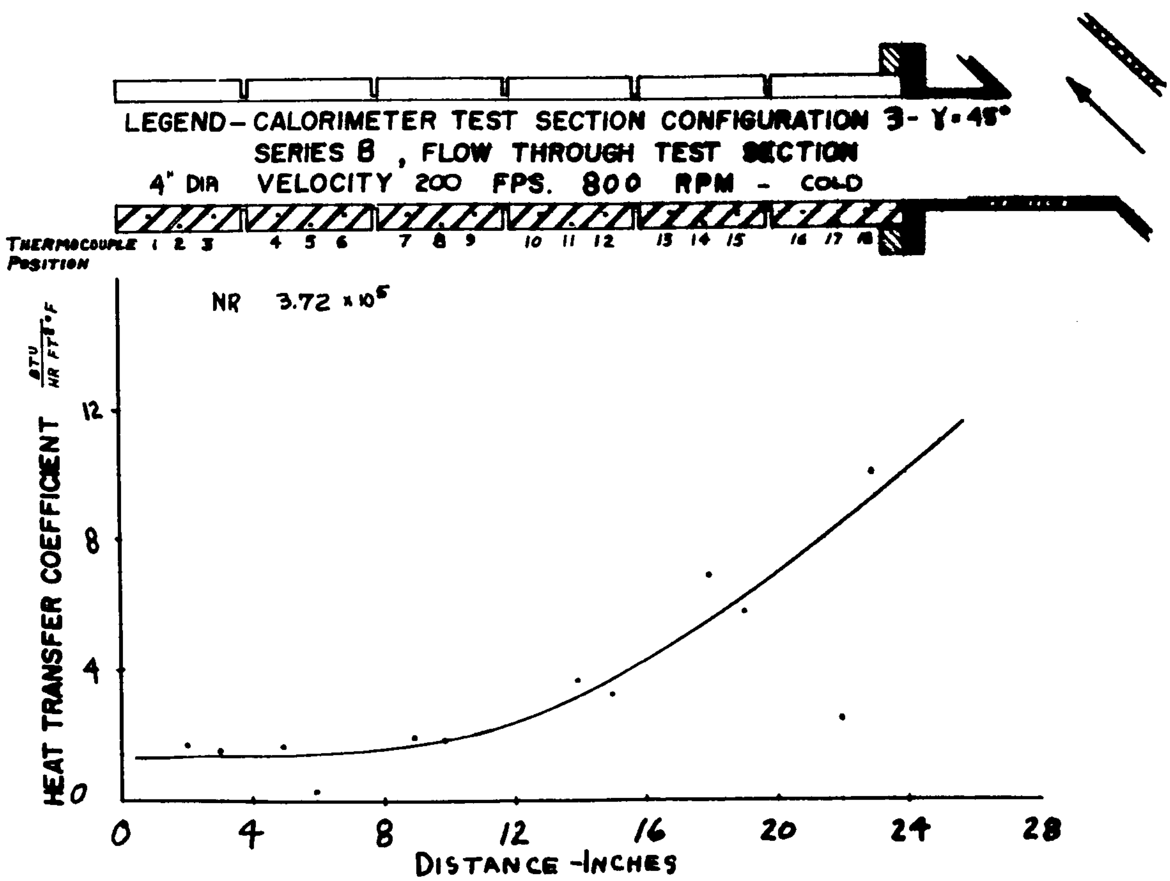


FIGURE A-8

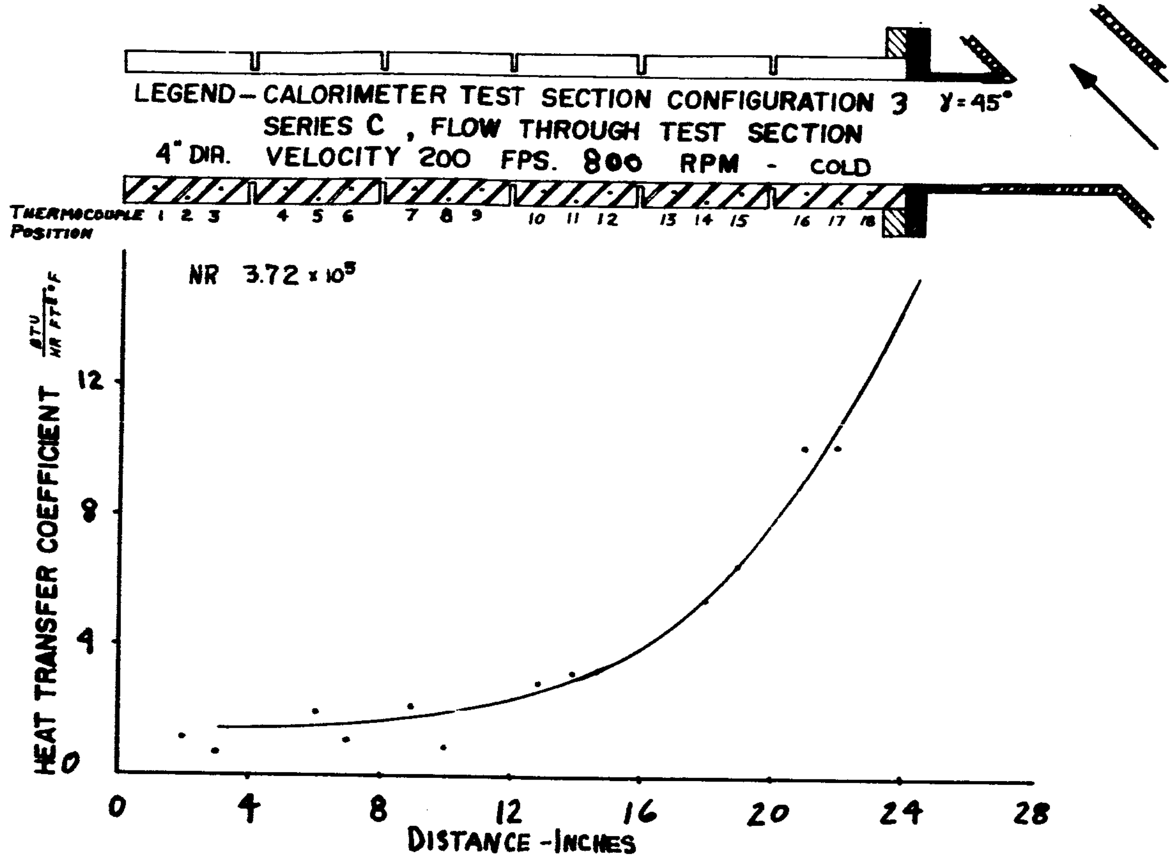


FIGURE A-9

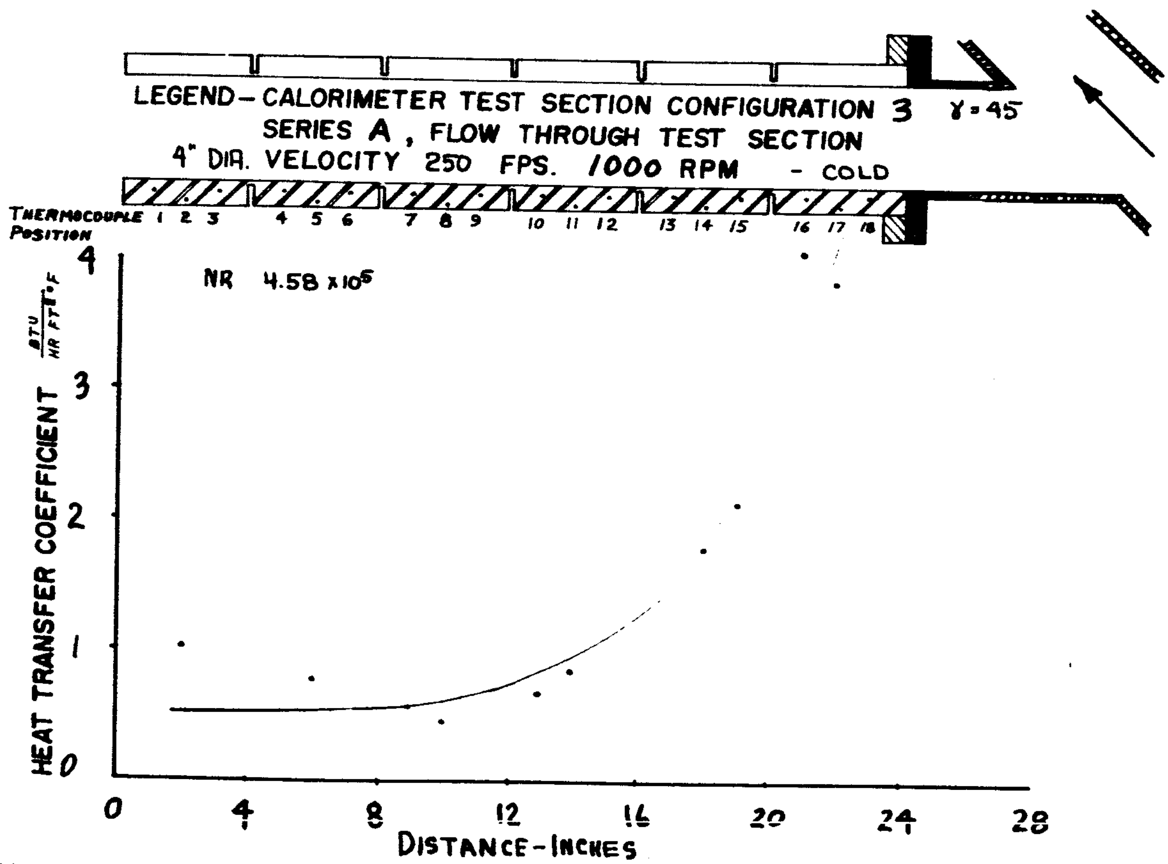


FIGURE A-10

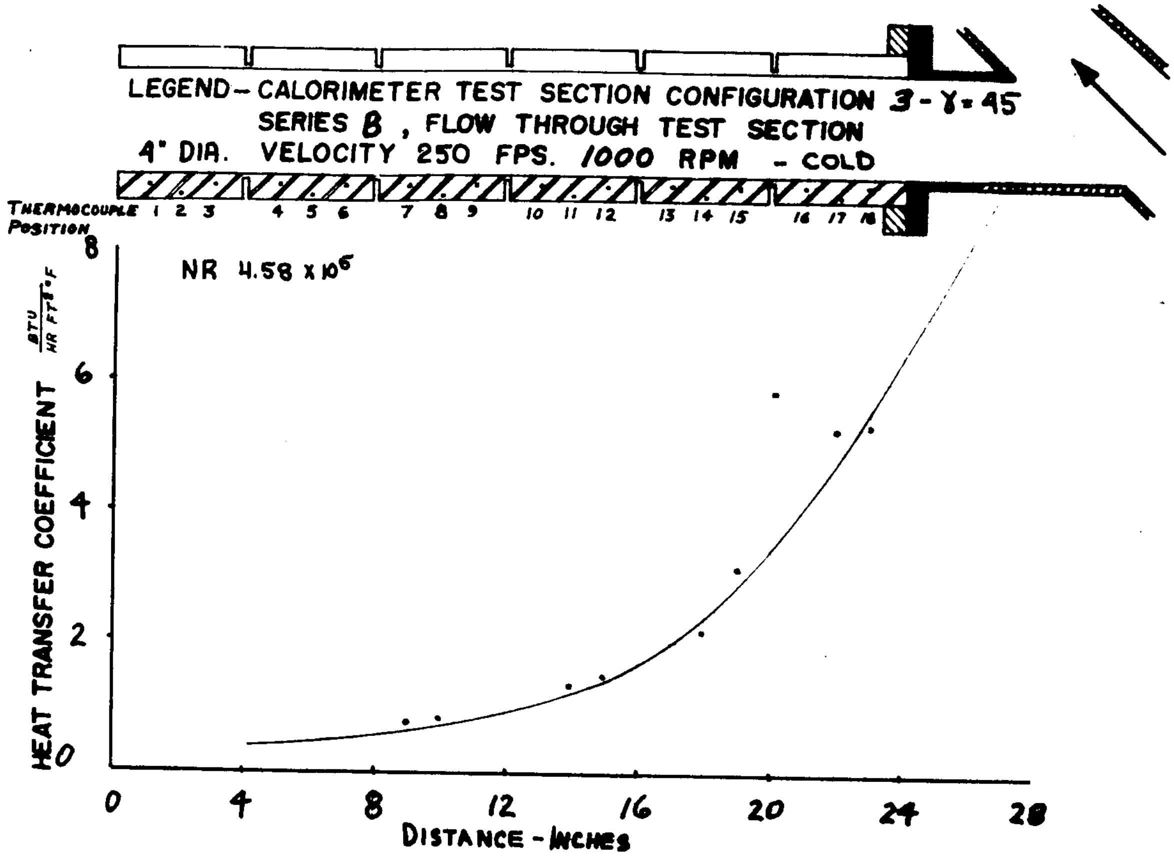


FIGURE A-11

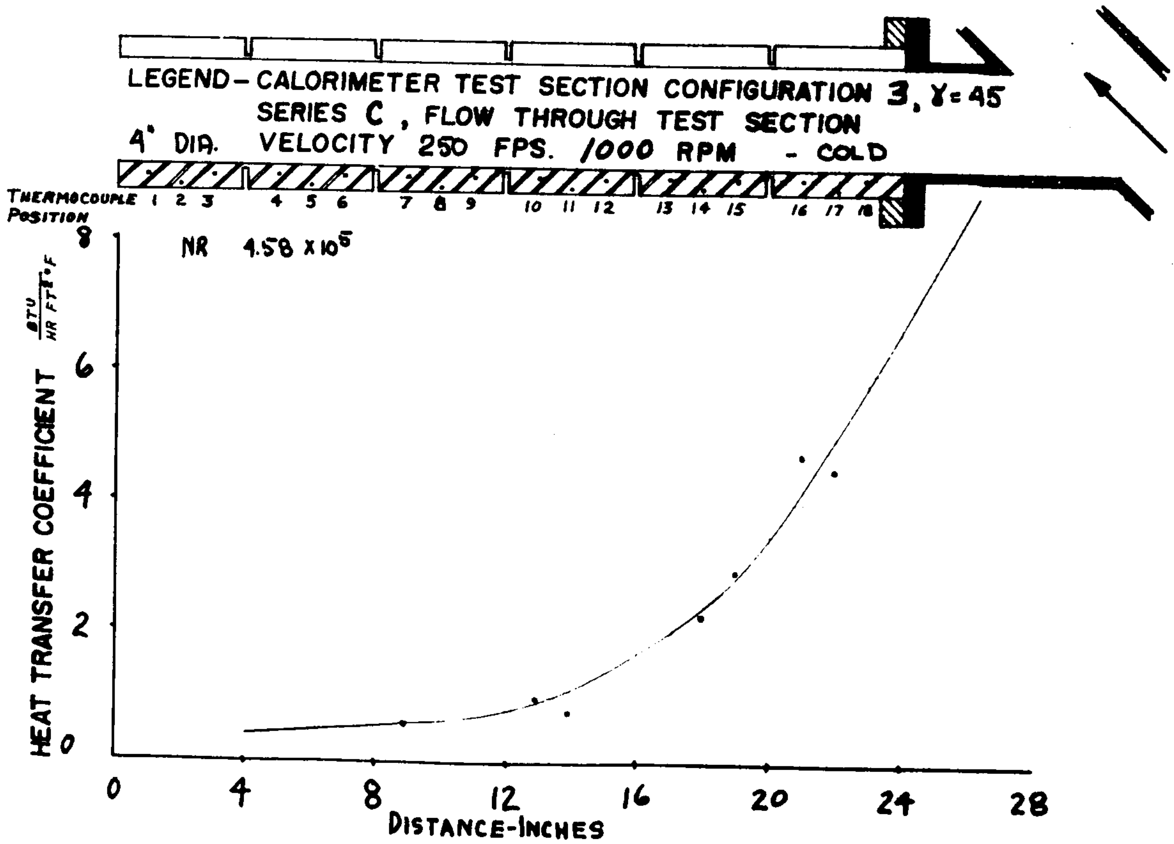


FIGURE A-12

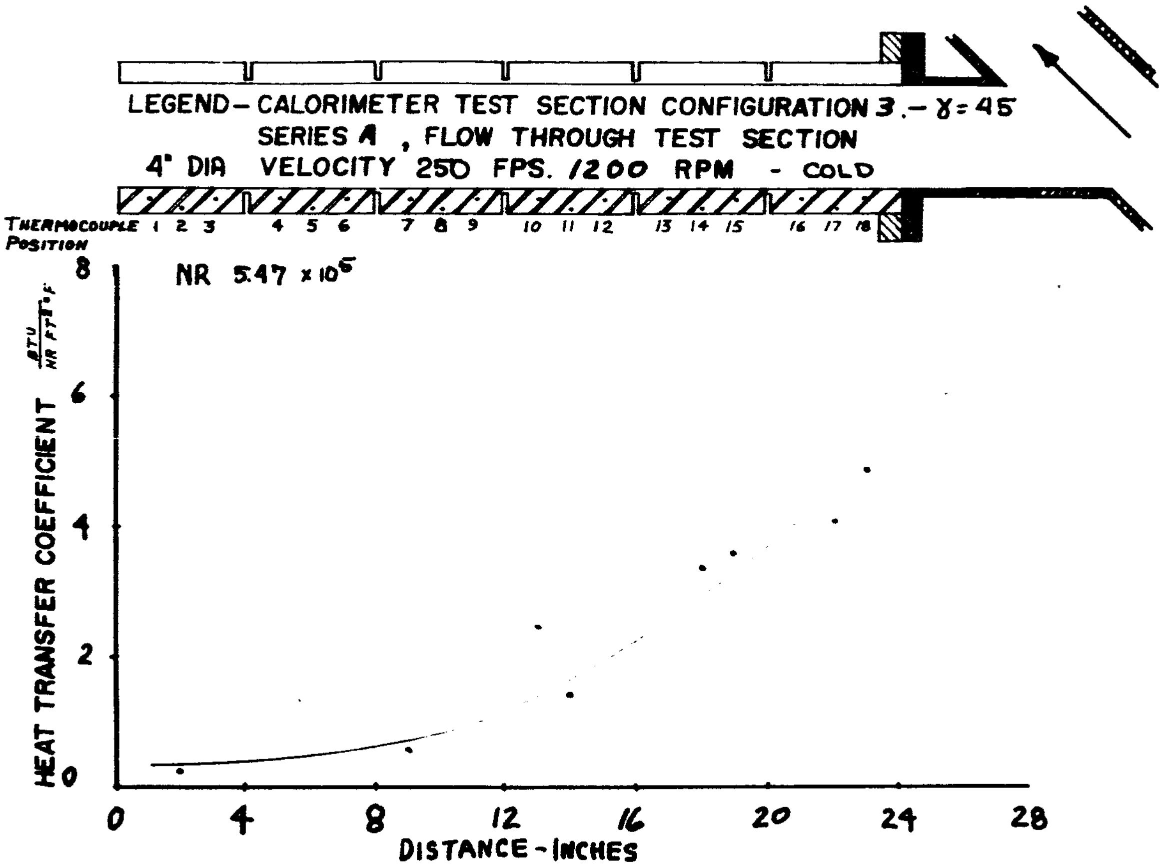


FIGURE A-13

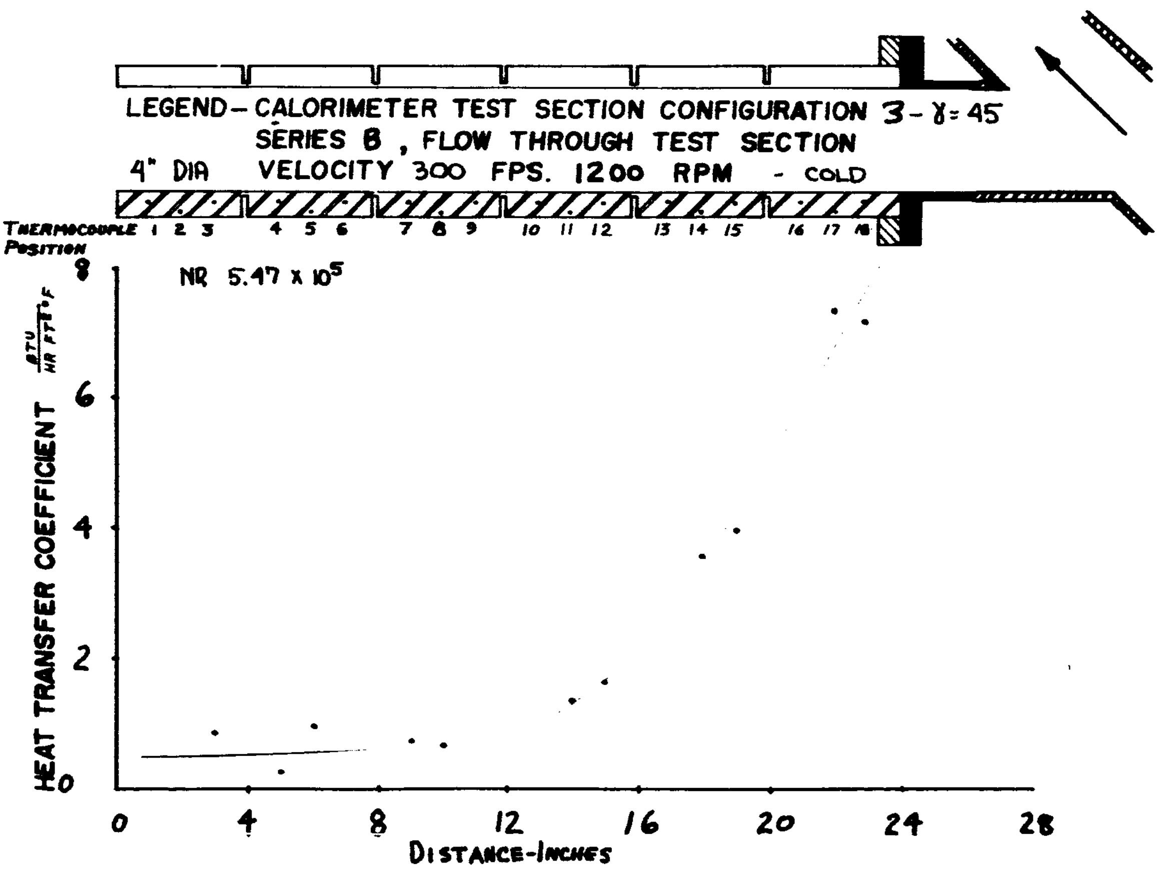


FIGURE A-14

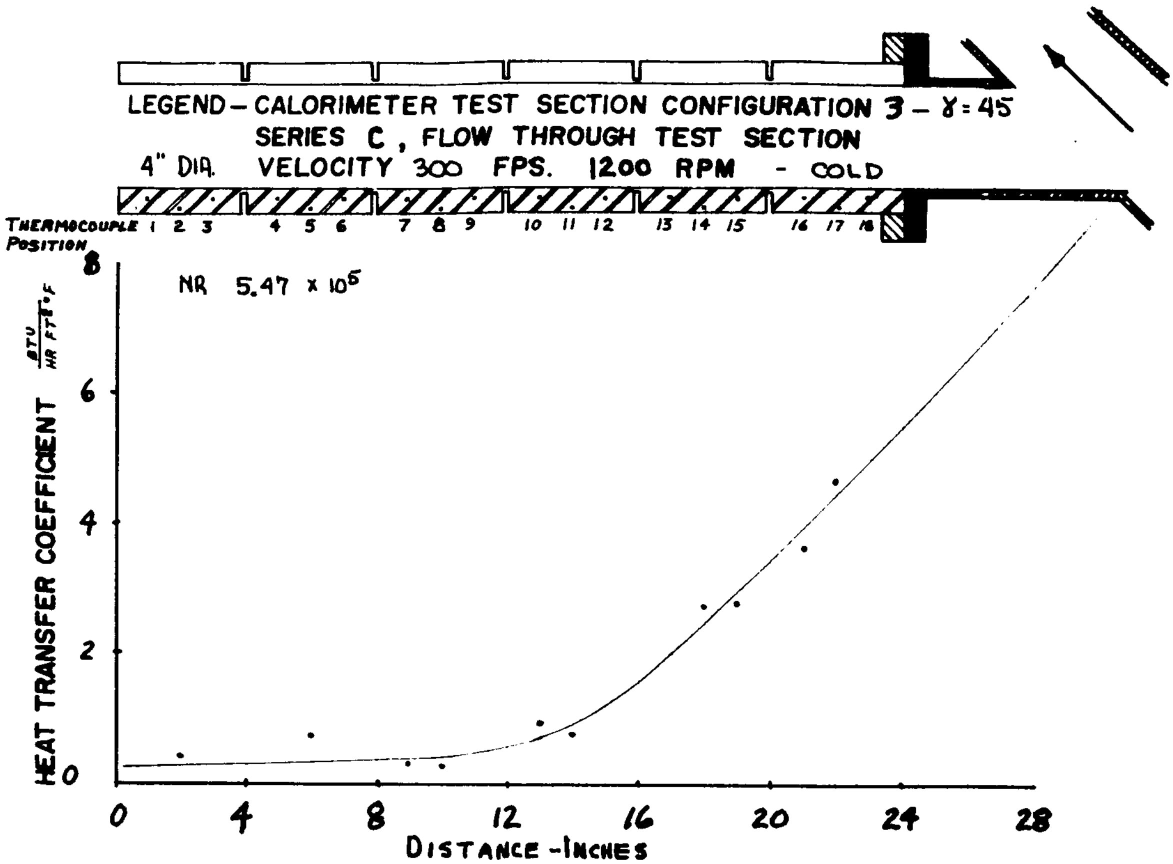


FIGURE A-15

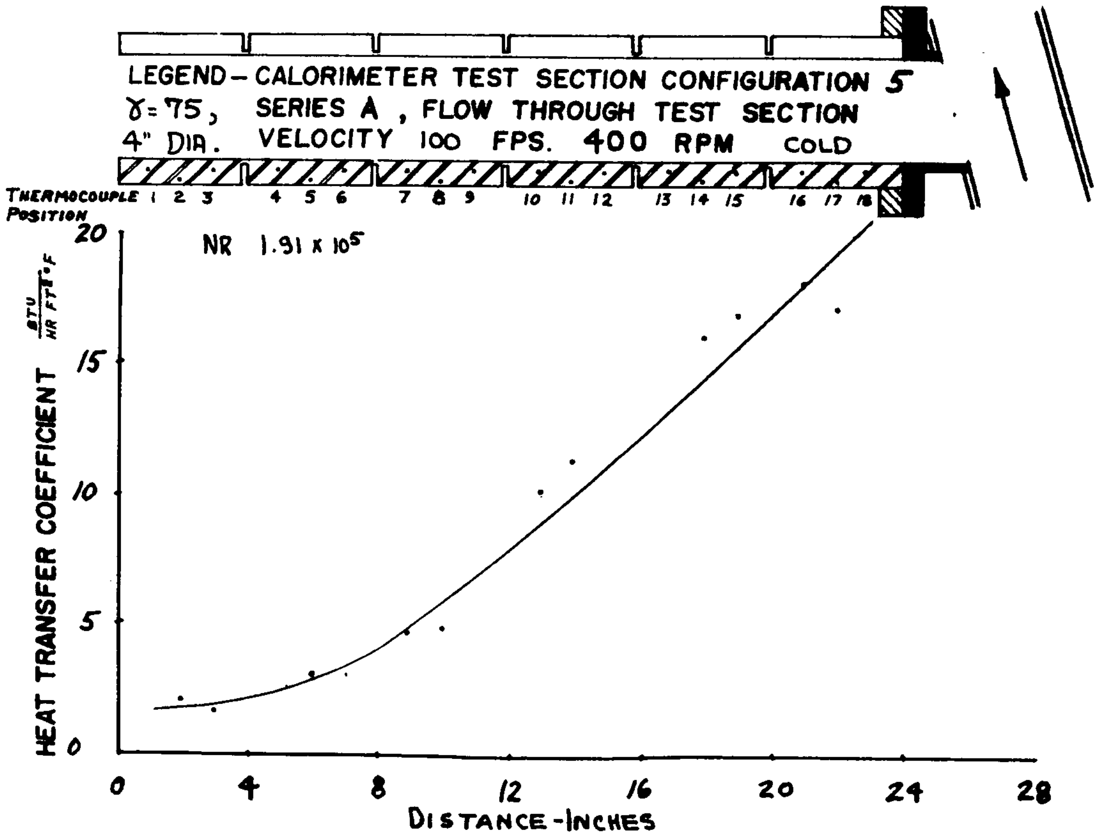


FIGURE A-16

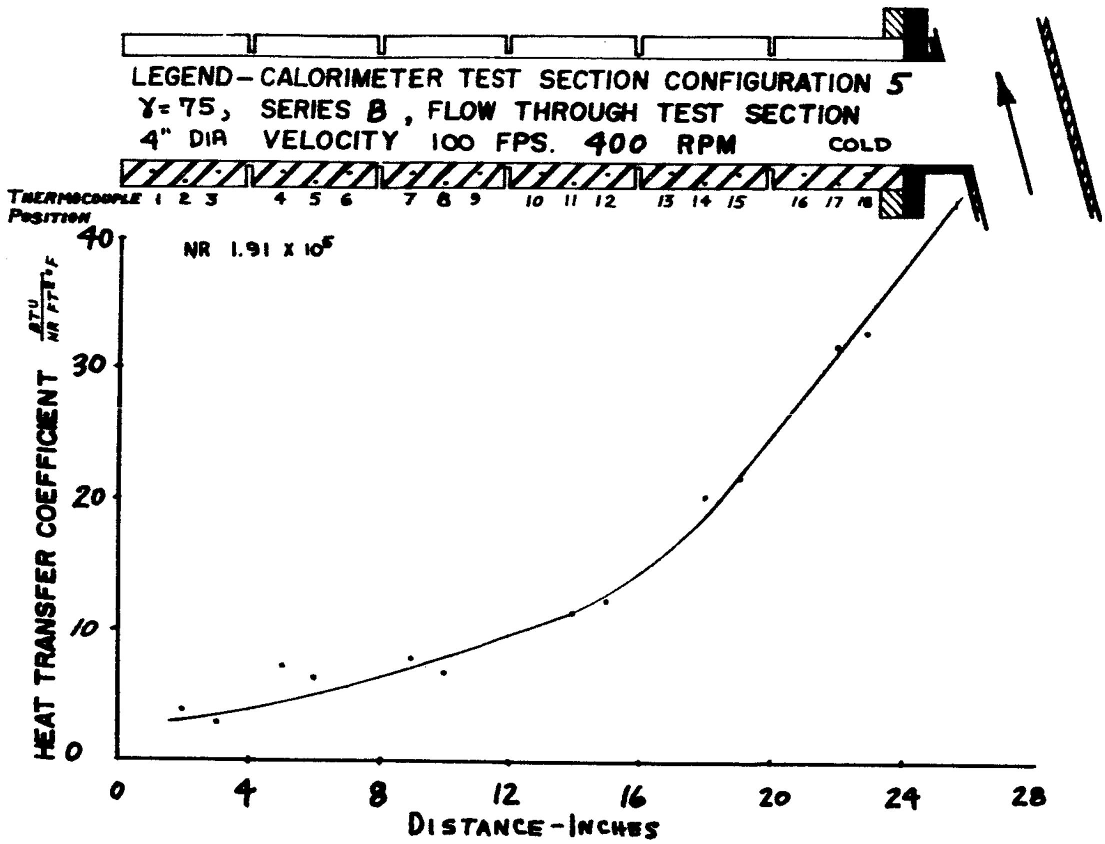


FIGURE A-17

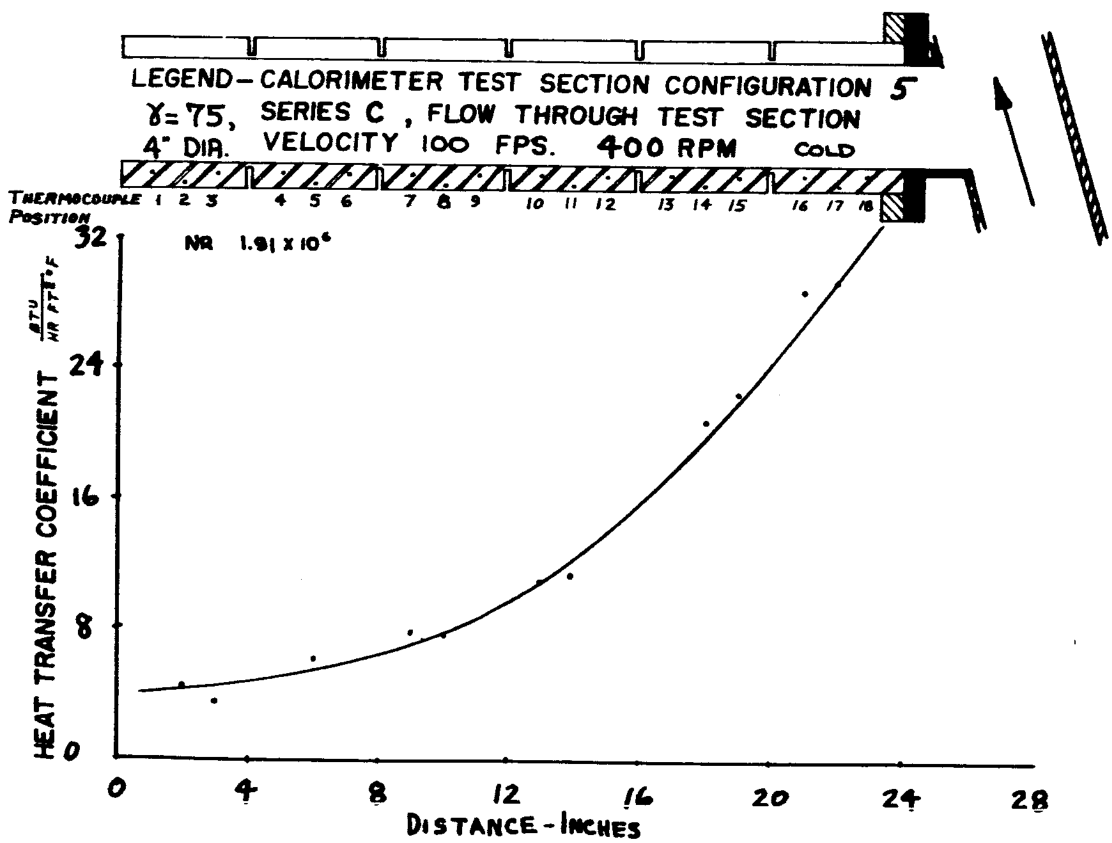


FIGURE A-18

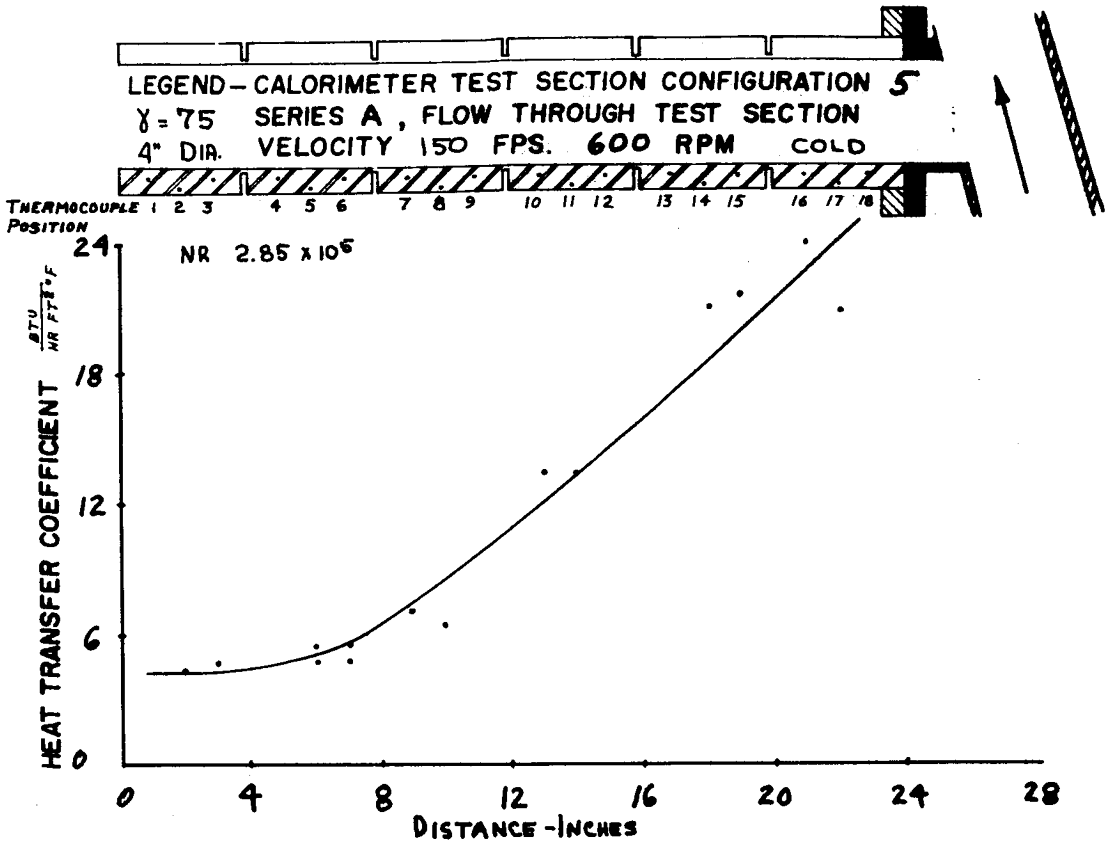


FIGURE A-19

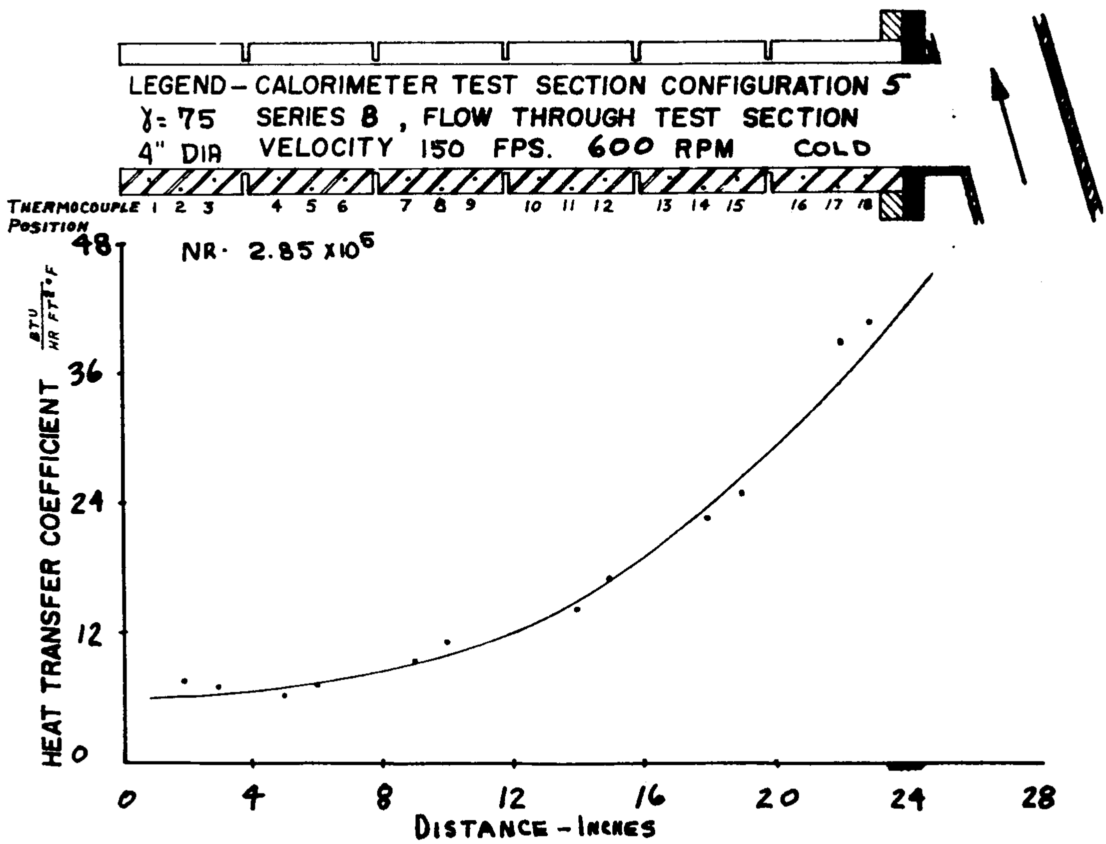


FIGURE A-20

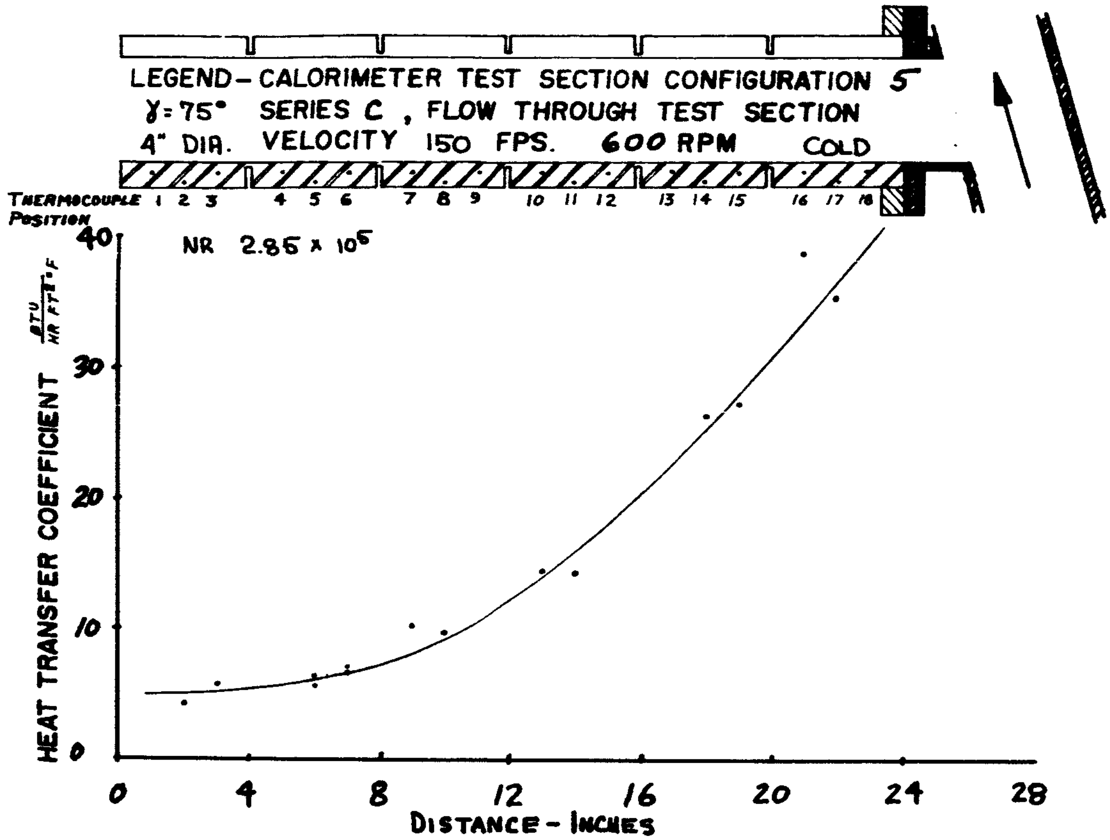


FIGURE A-21

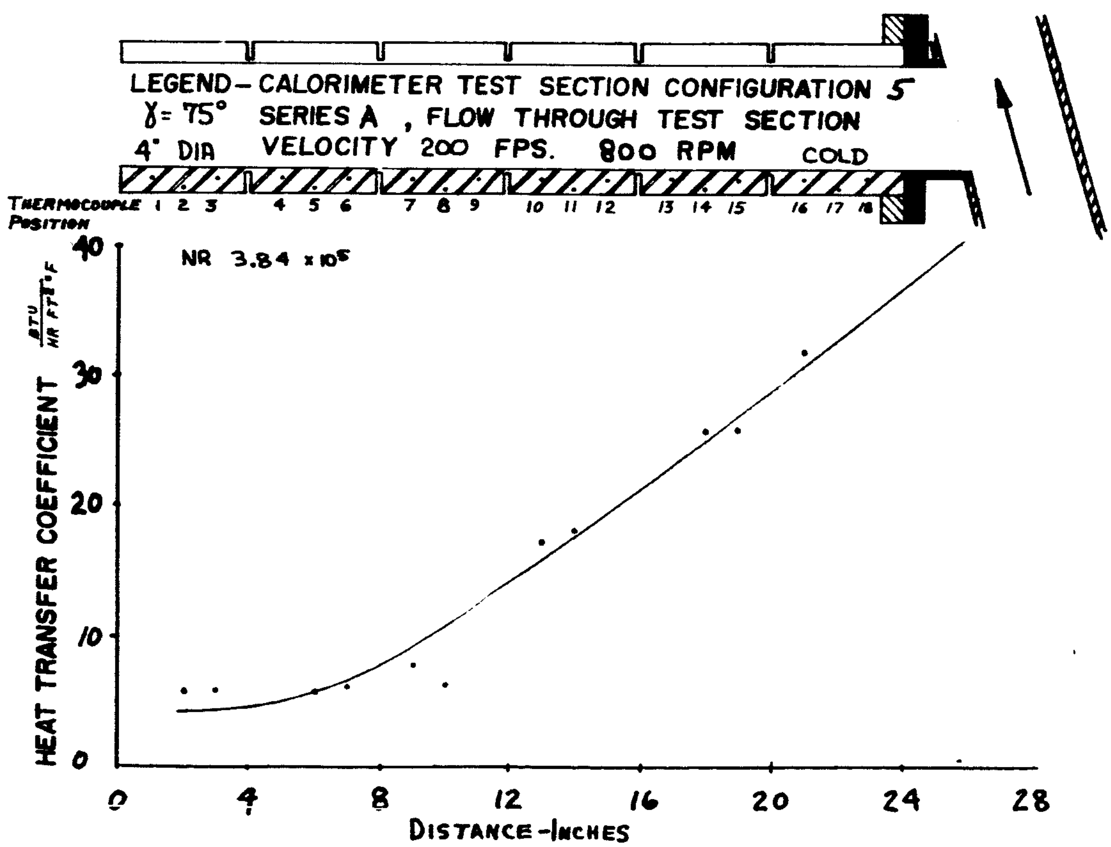


FIGURE A-22

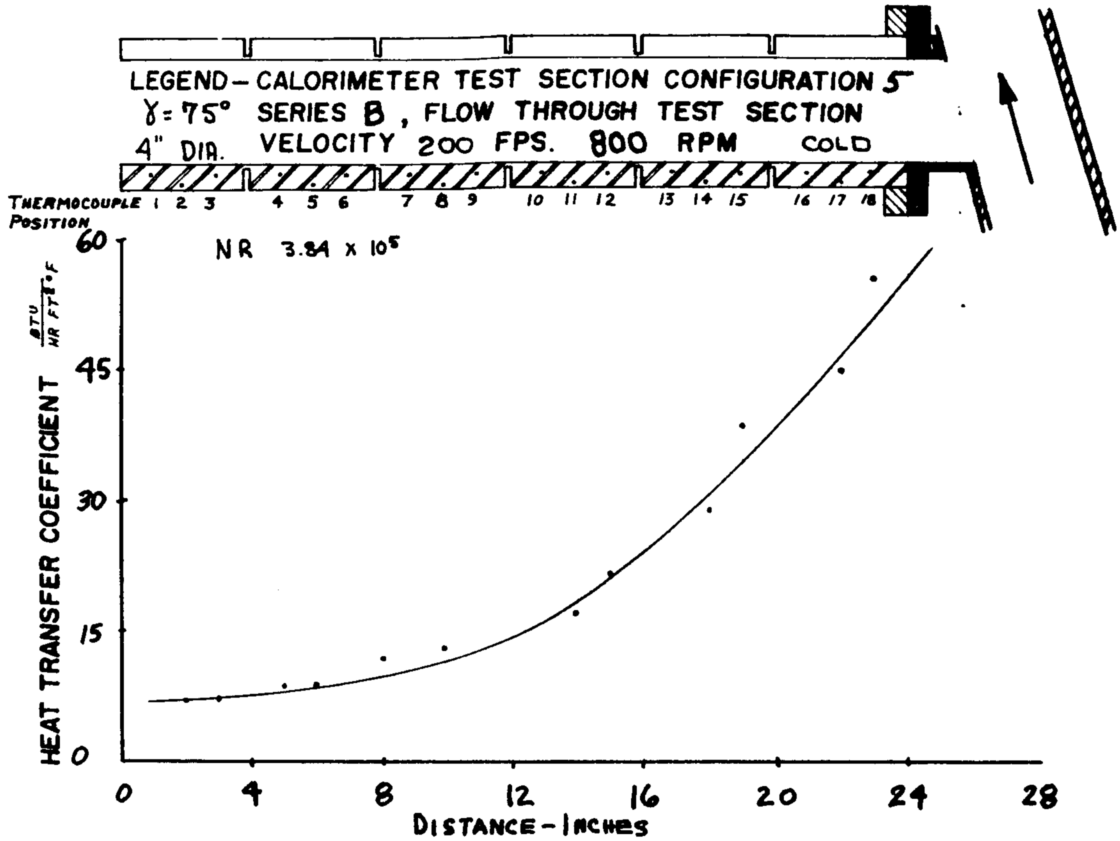


FIGURE A-23

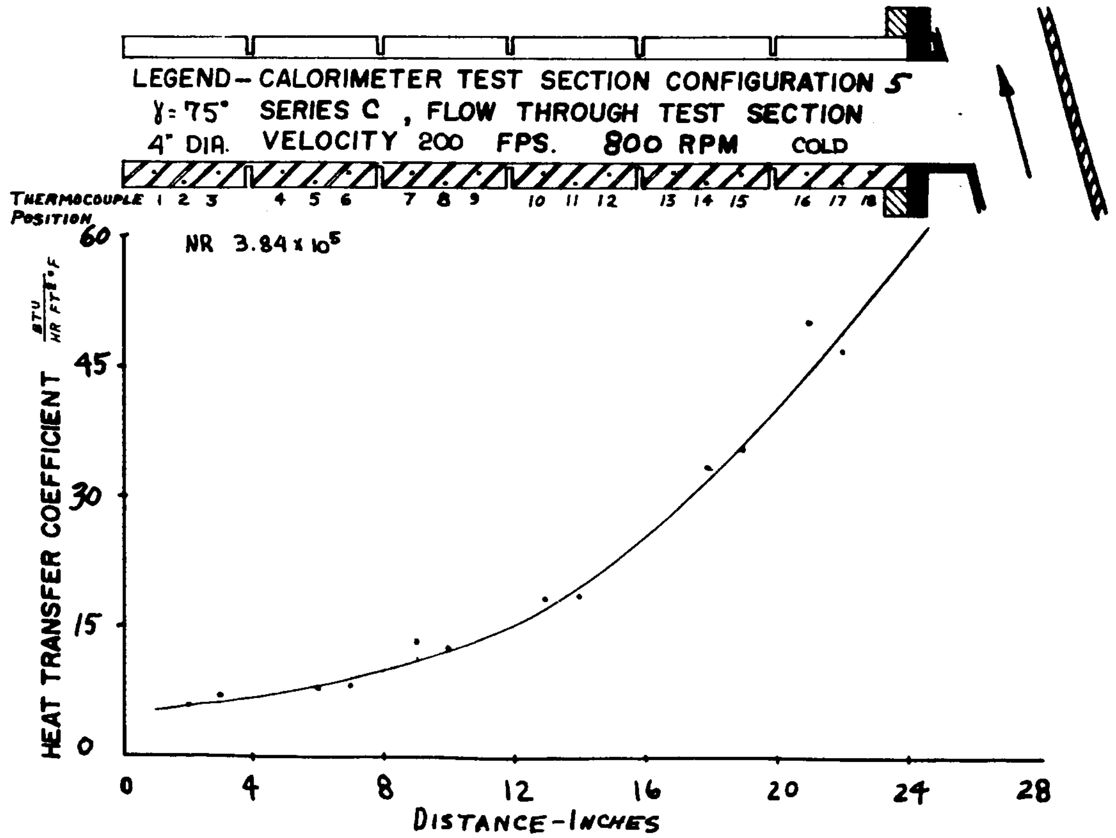


FIGURE A-24

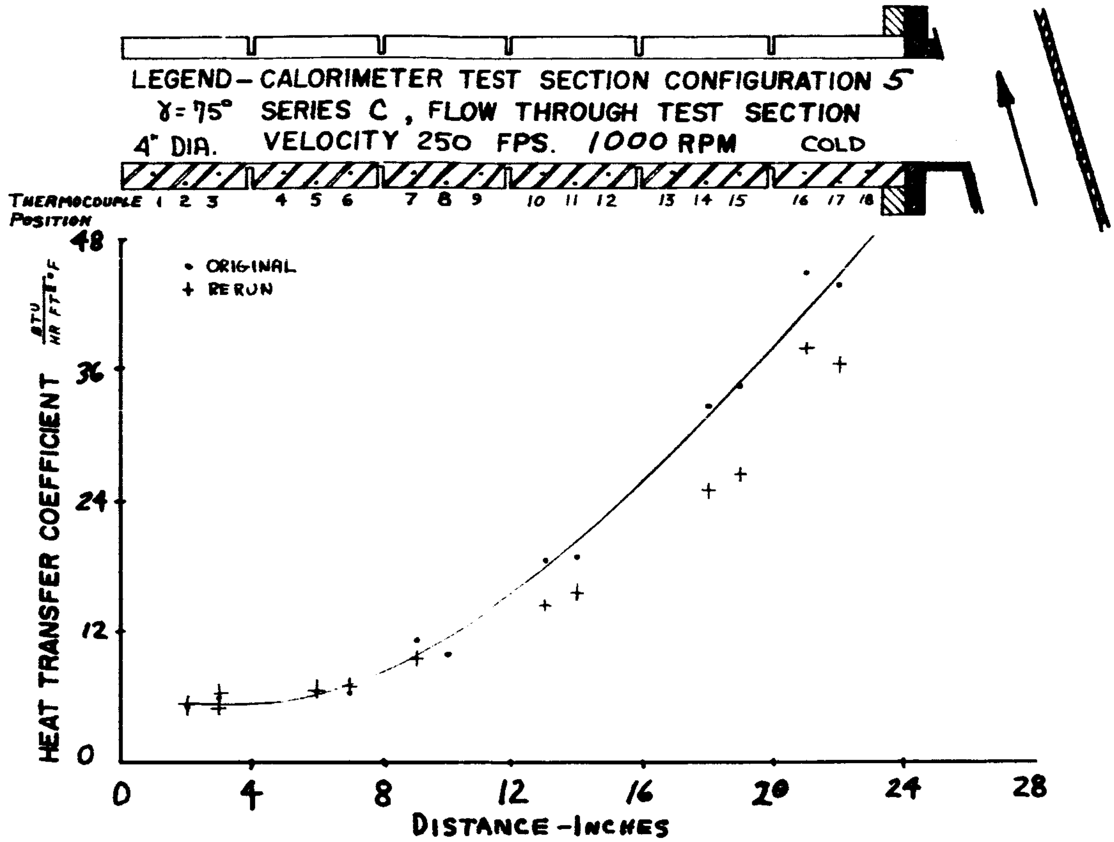


FIGURE A-25

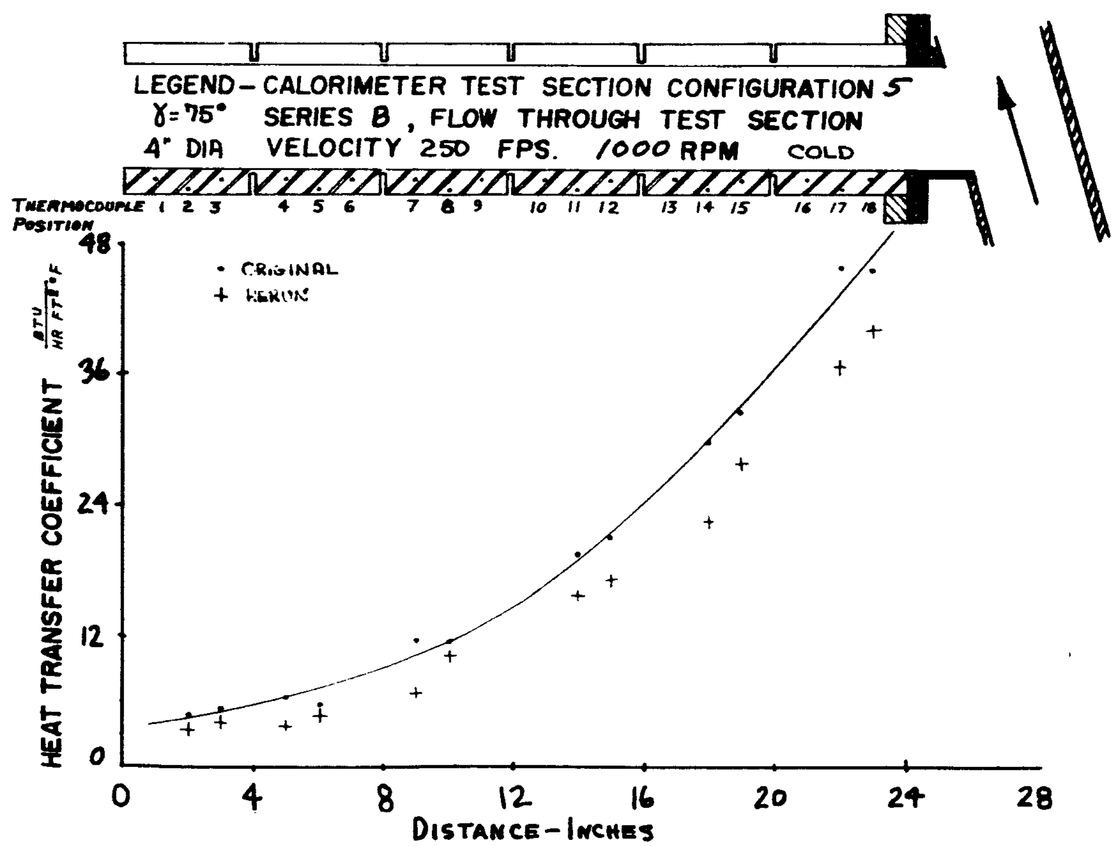


FIGURE A-26

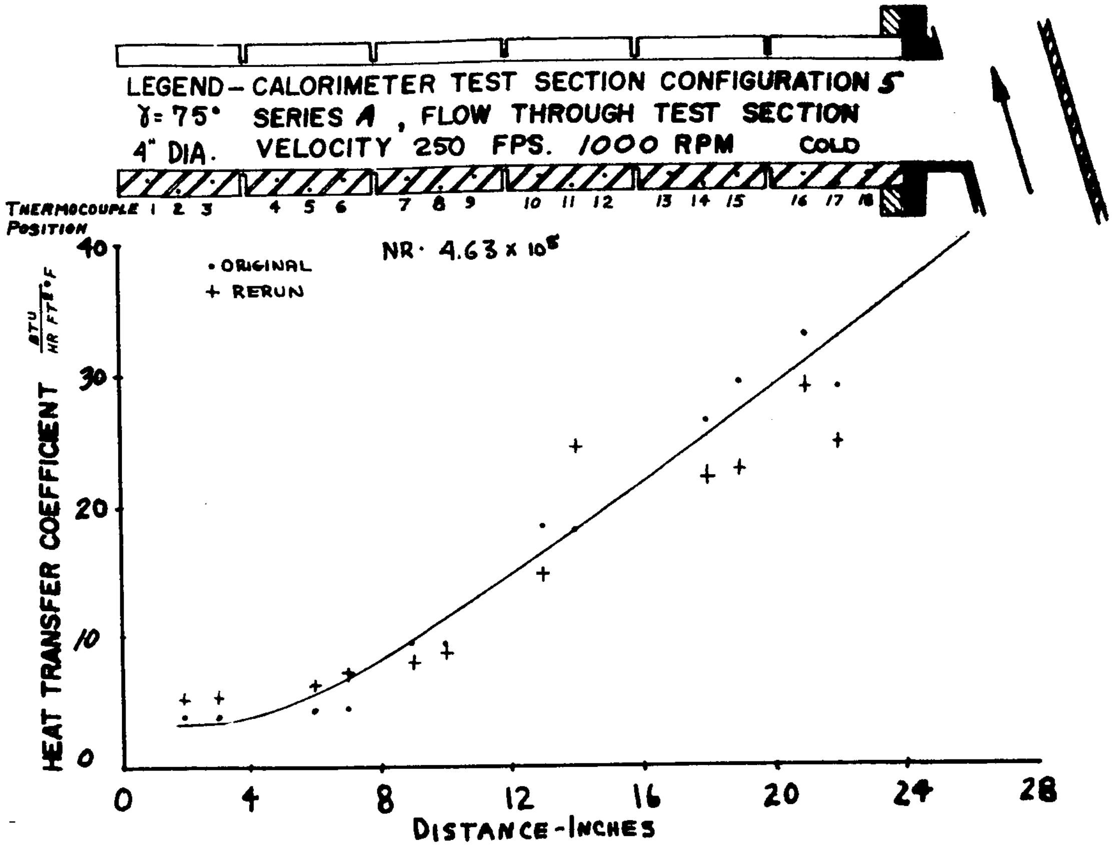


FIGURE A-27

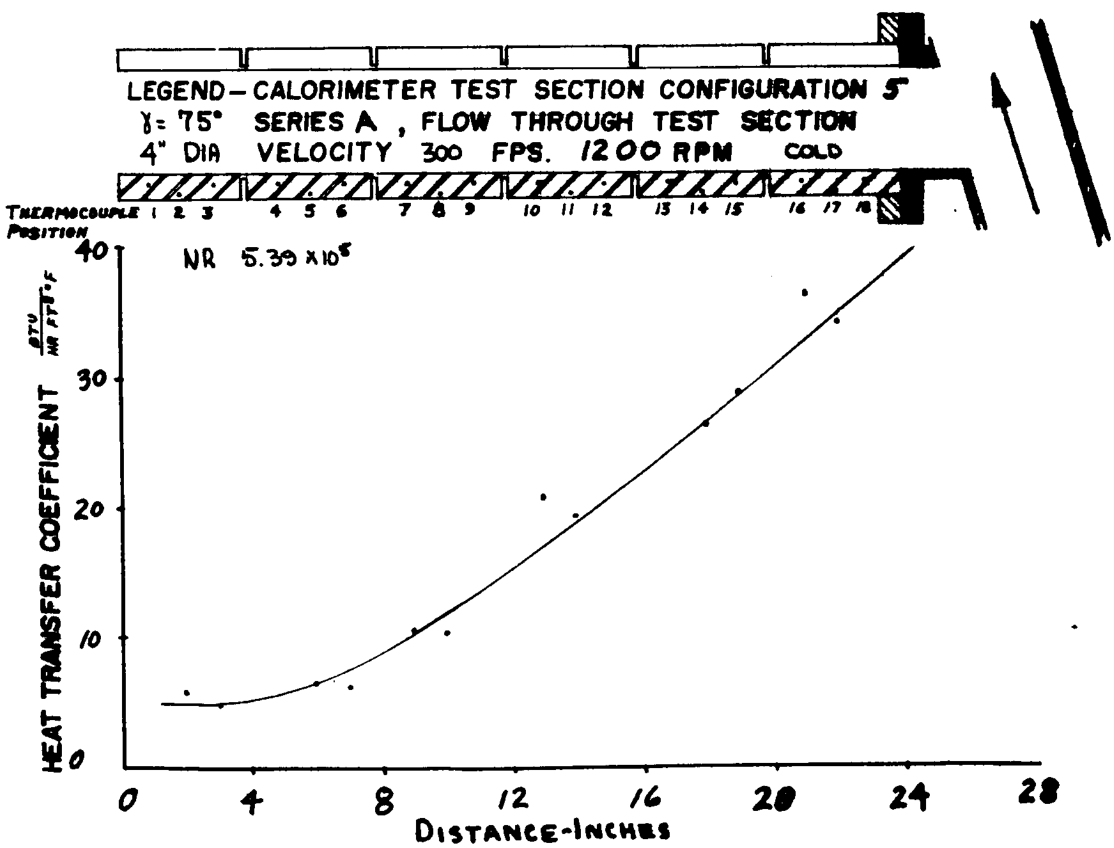


FIGURE A-28

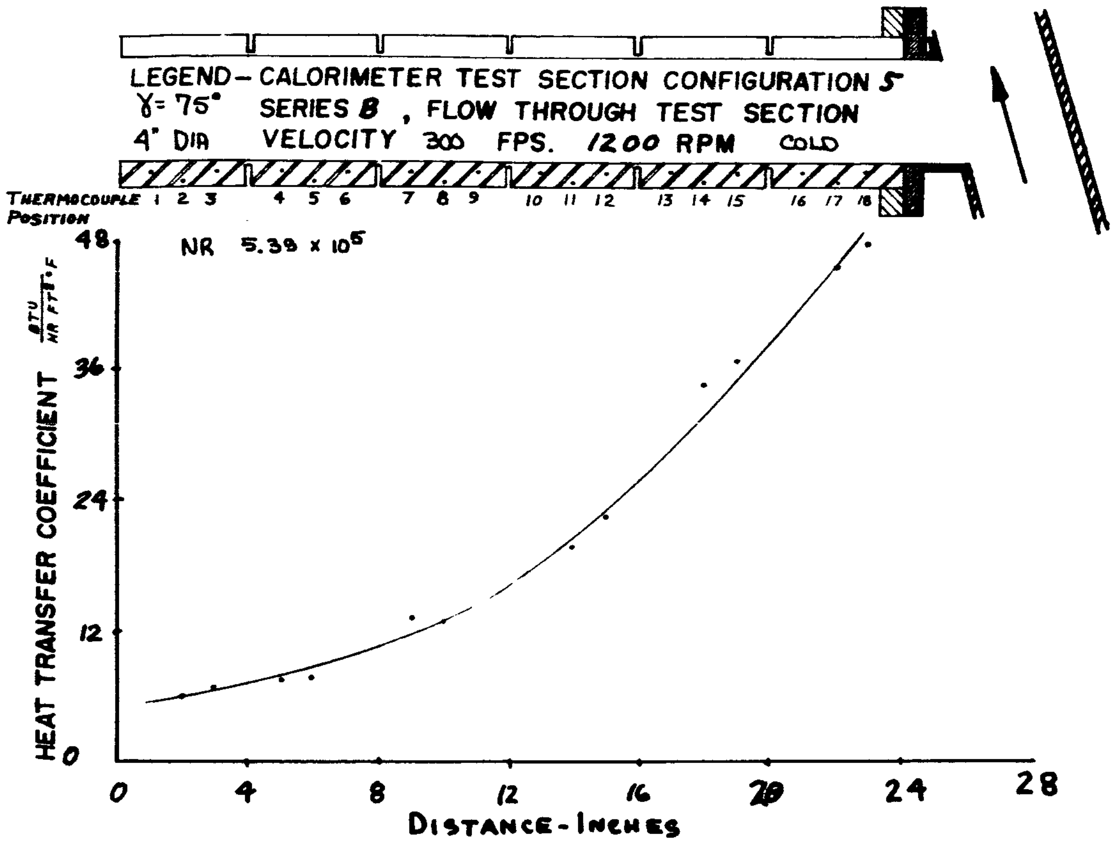


FIGURE A-29

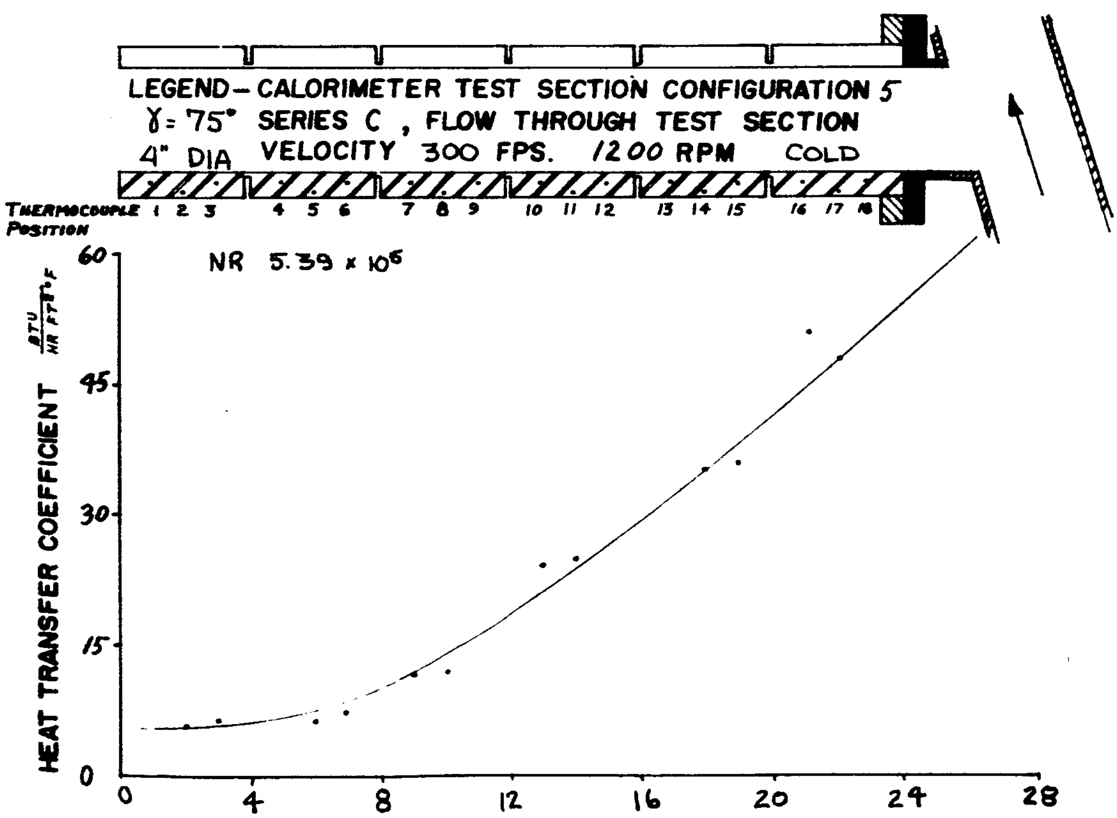


FIGURE A-30

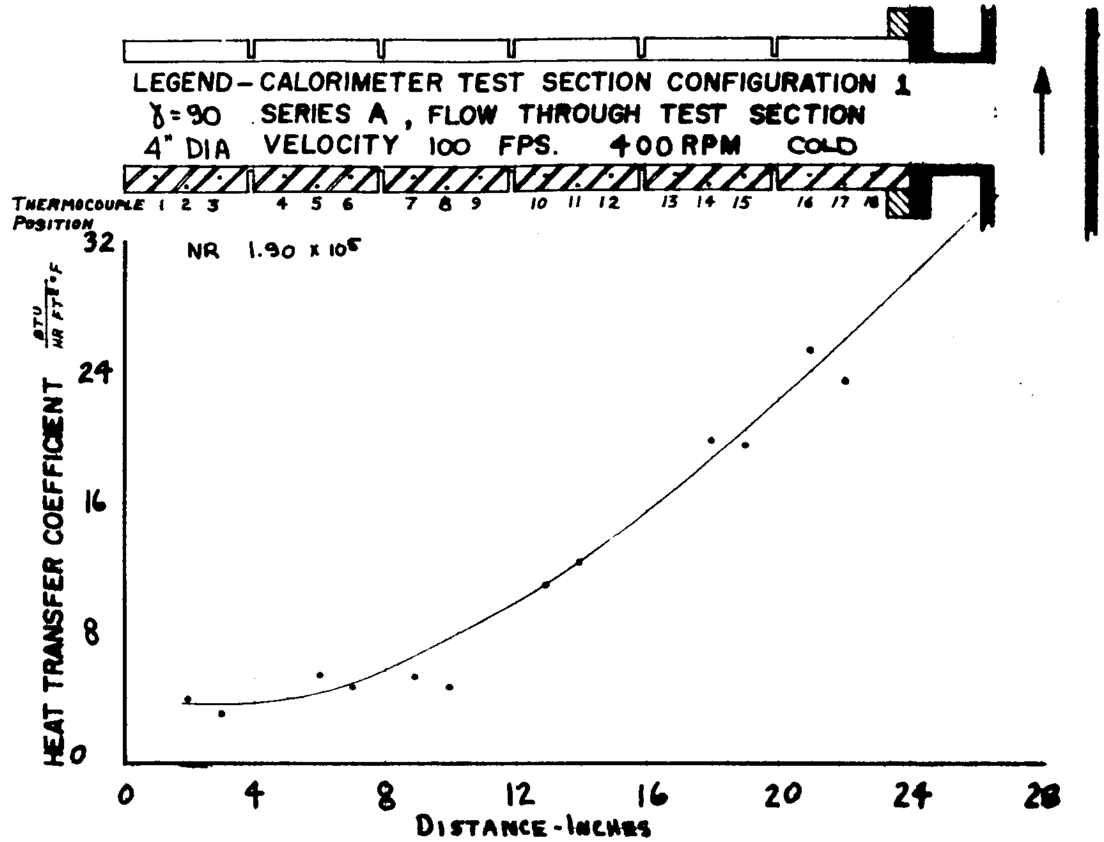


FIGURE A-31

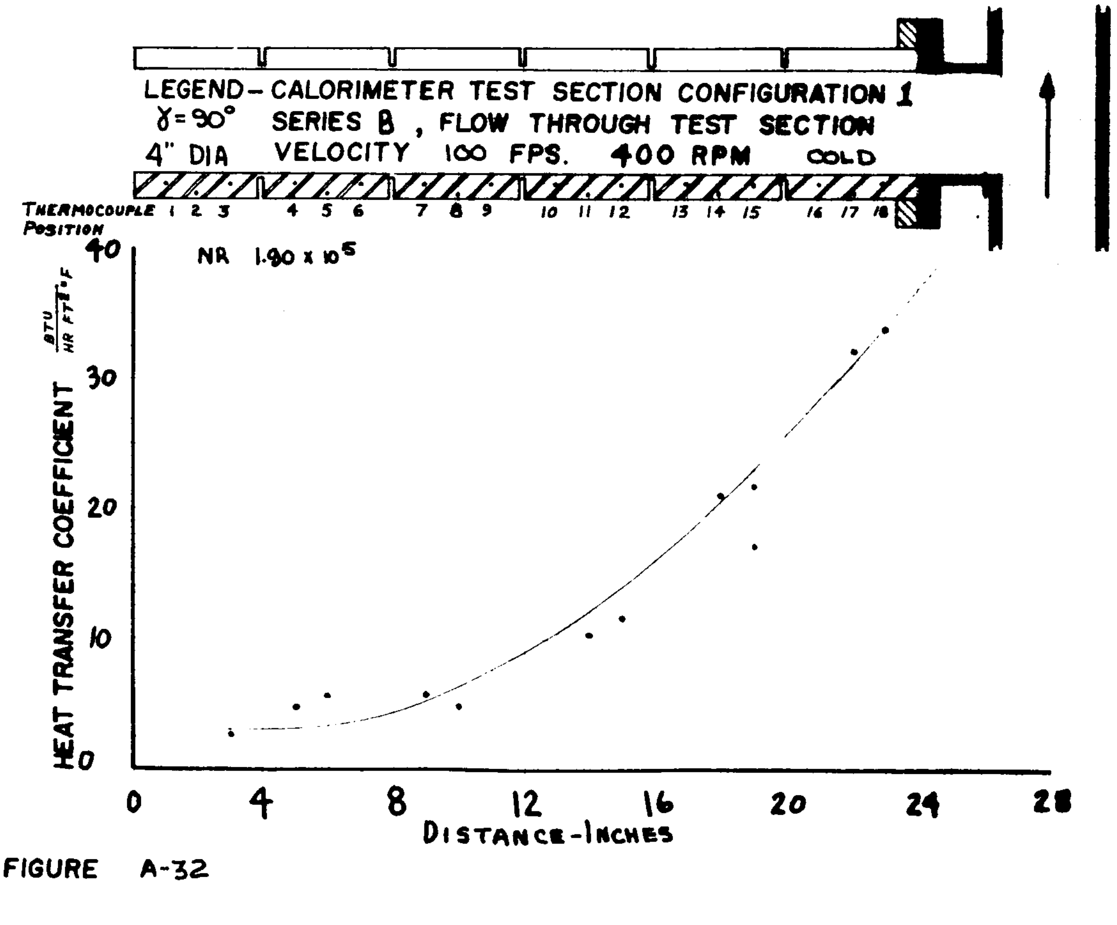


FIGURE A-32

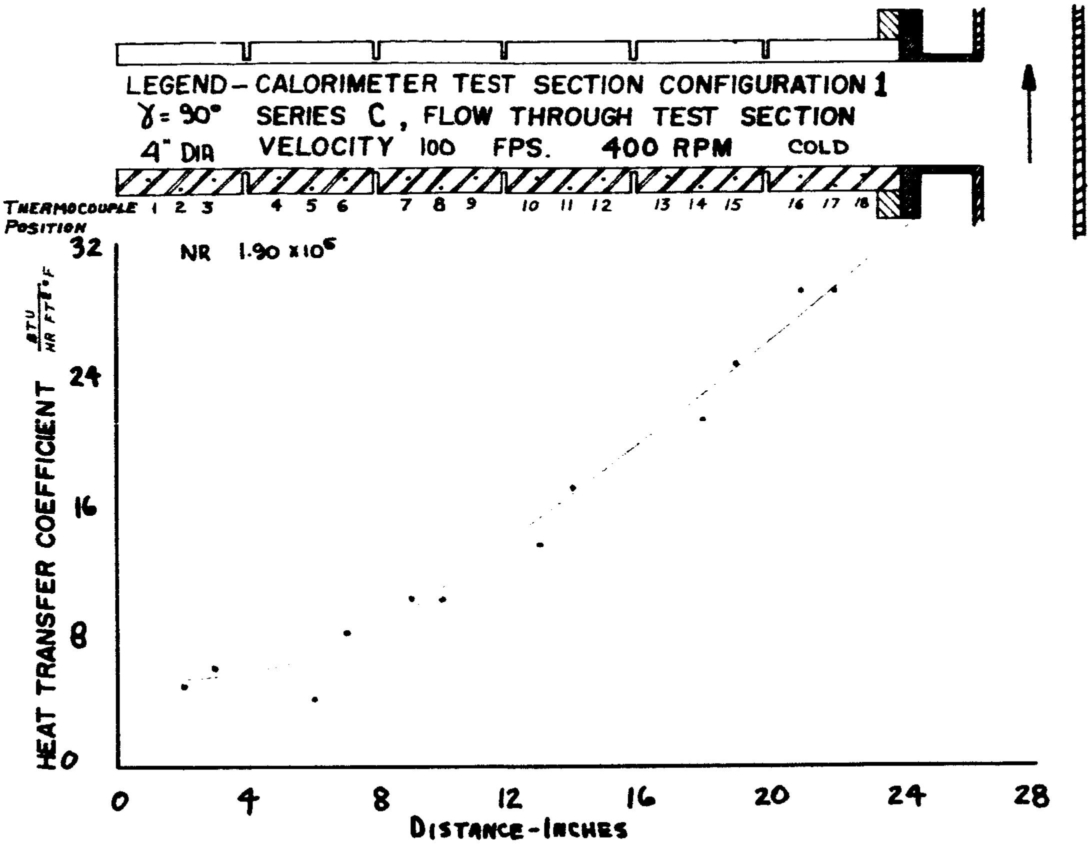


FIGURE A-33

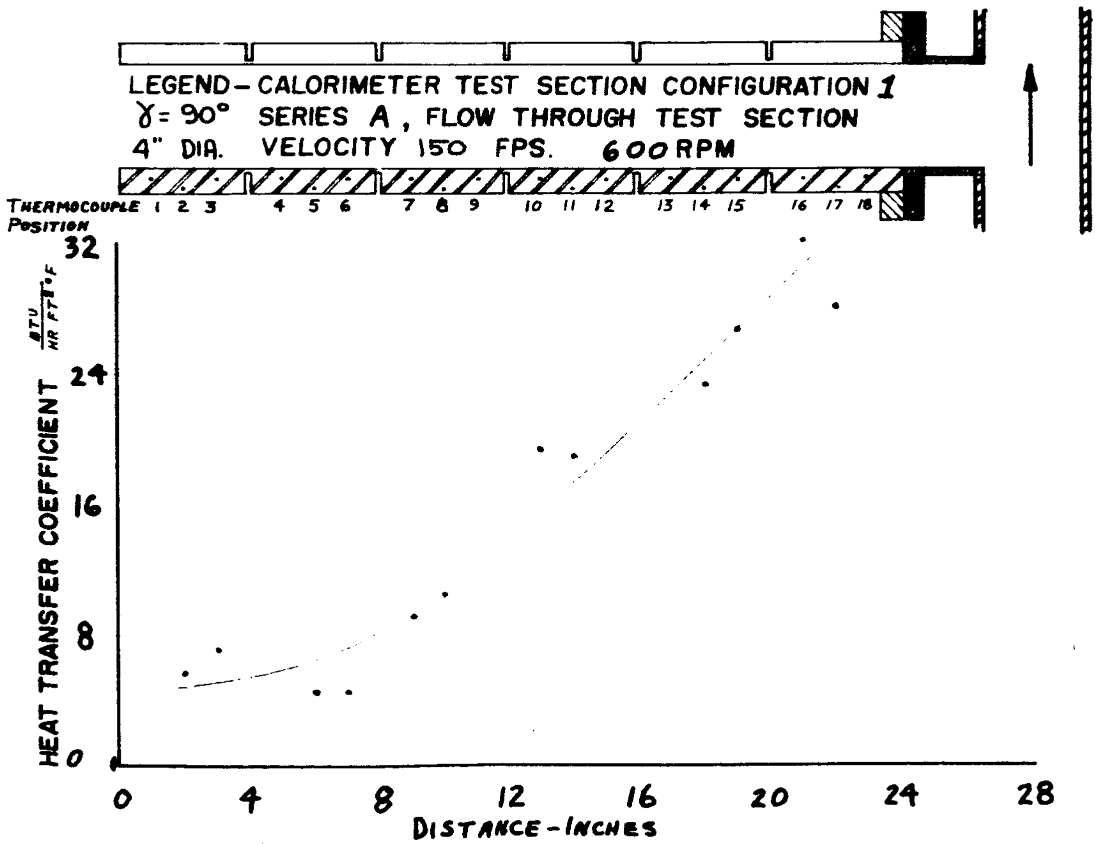


FIGURE A-34

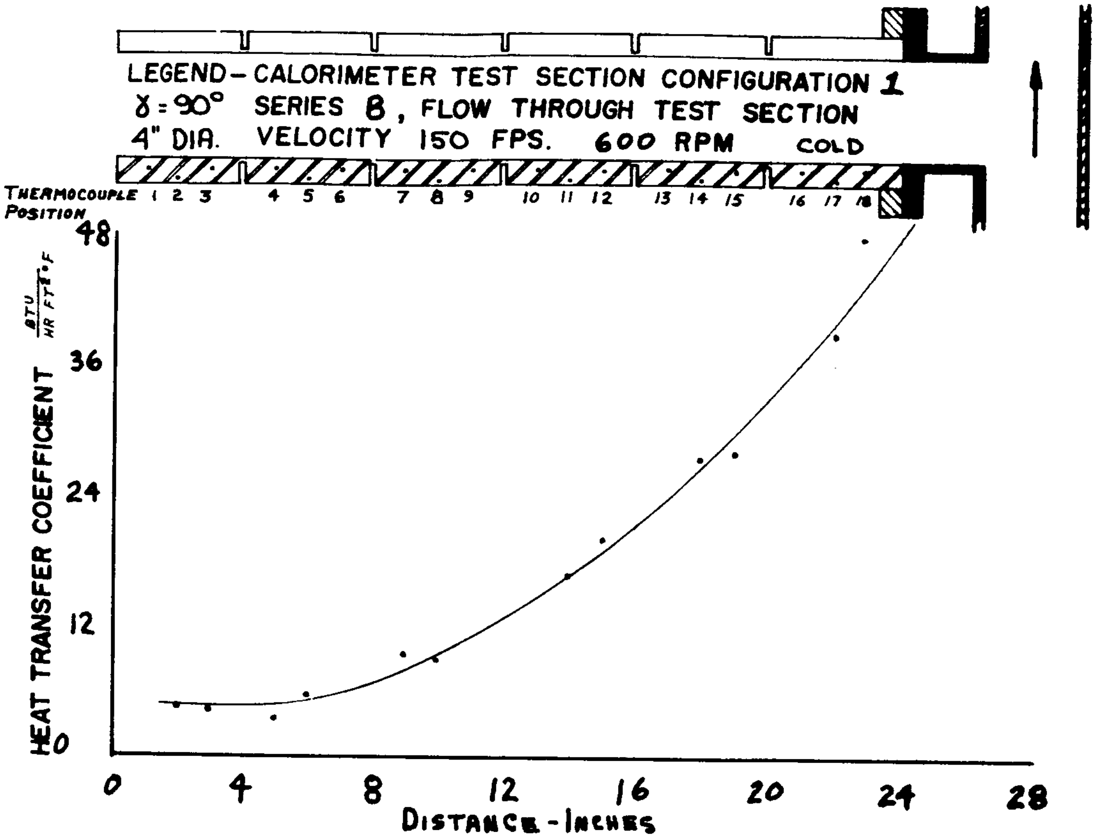


FIGURE A-35

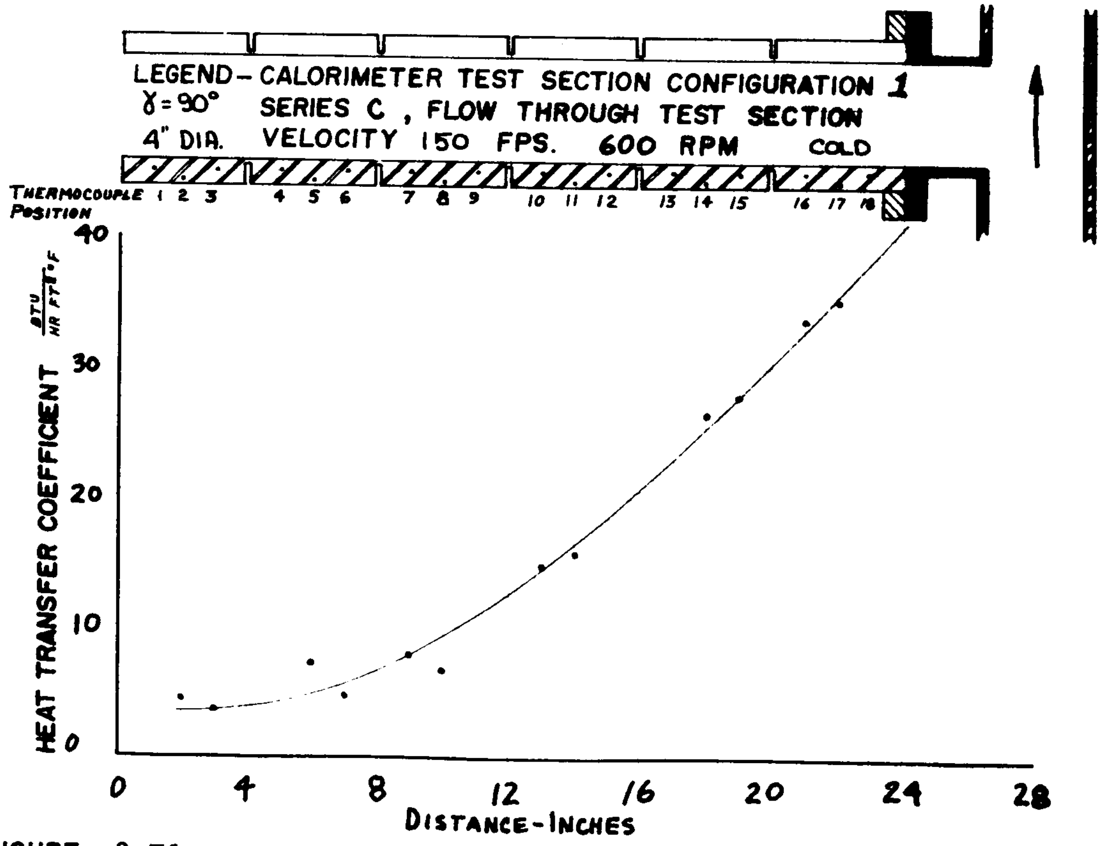


FIGURE A-36

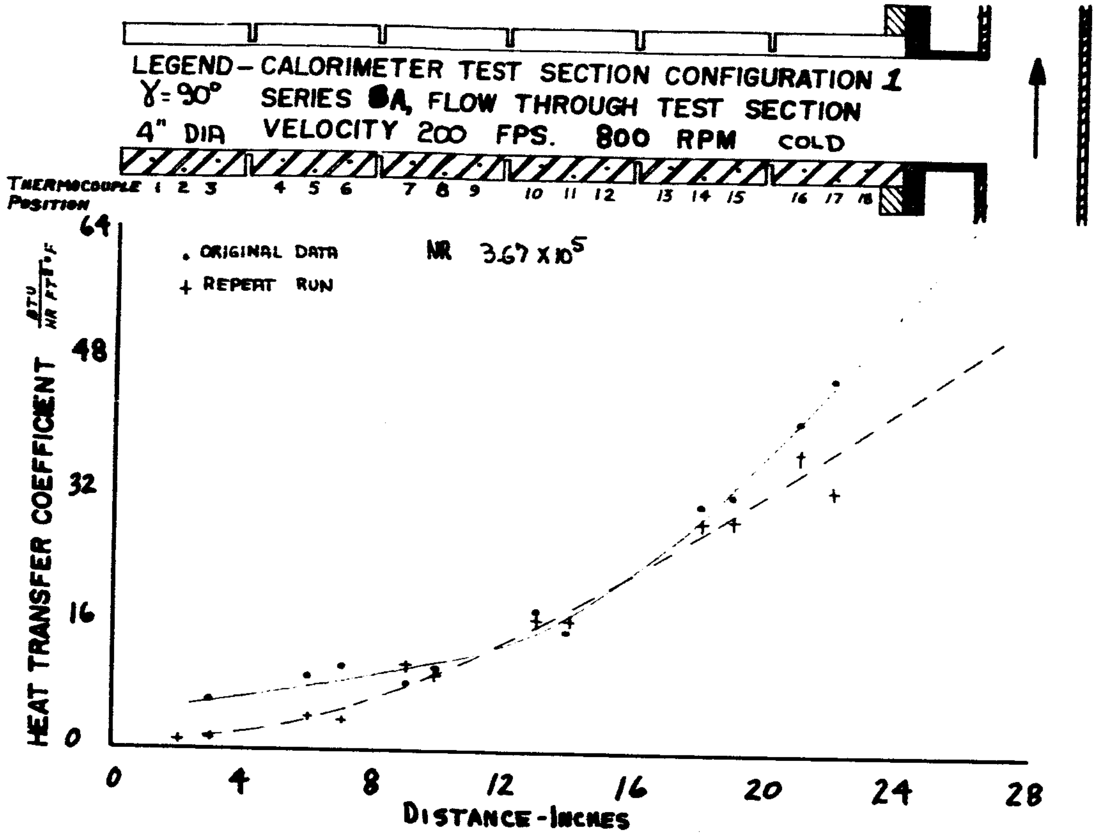


FIGURE A-37

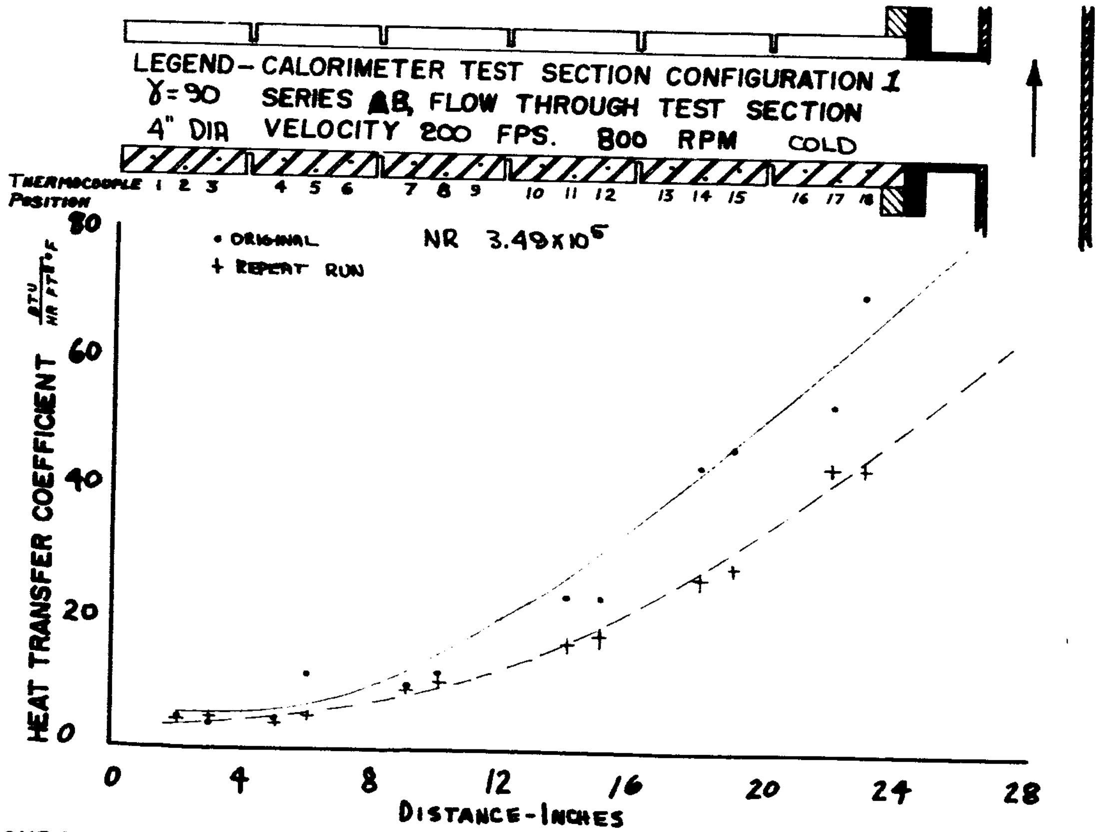


FIGURE A-38

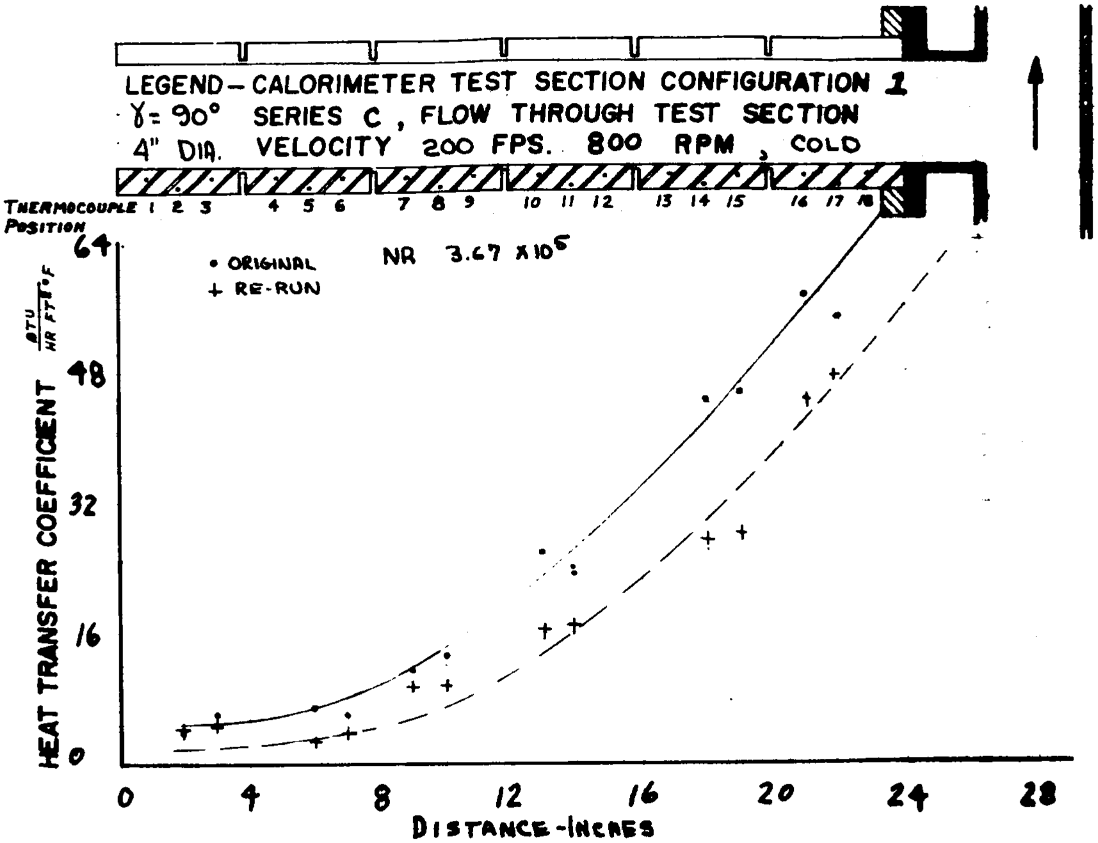


FIGURE A-39

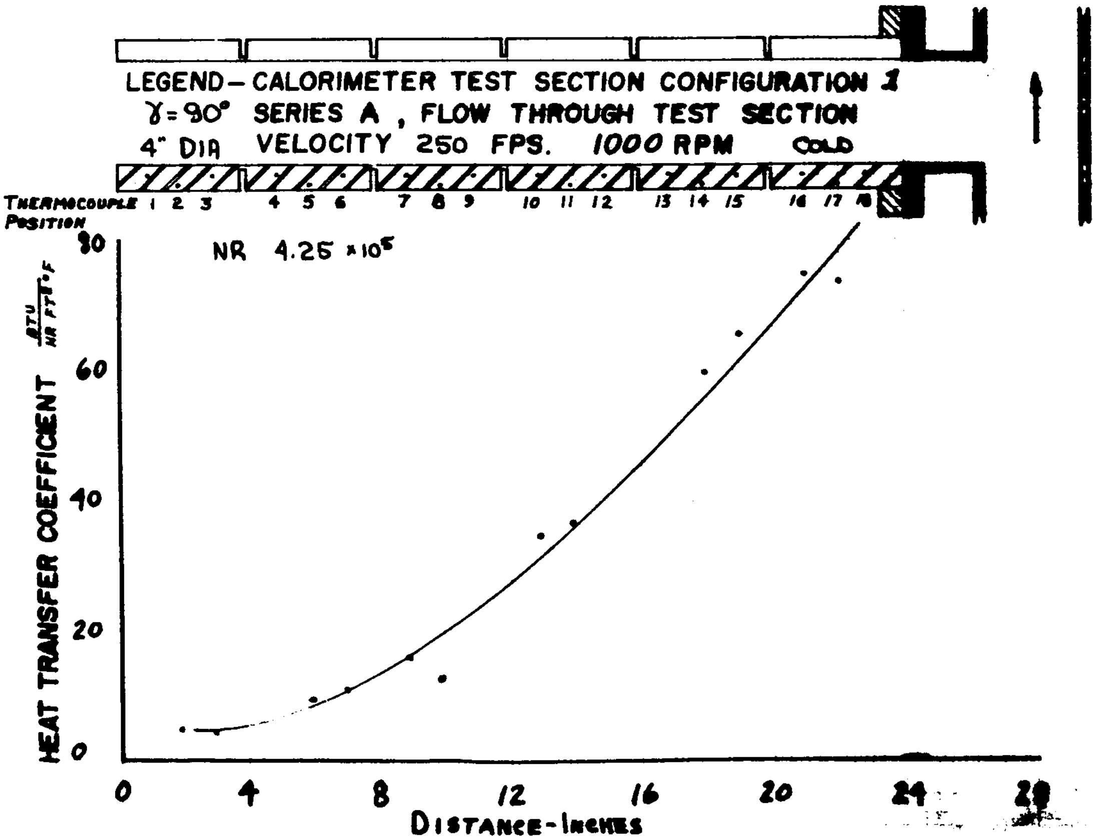


FIGURE A-40

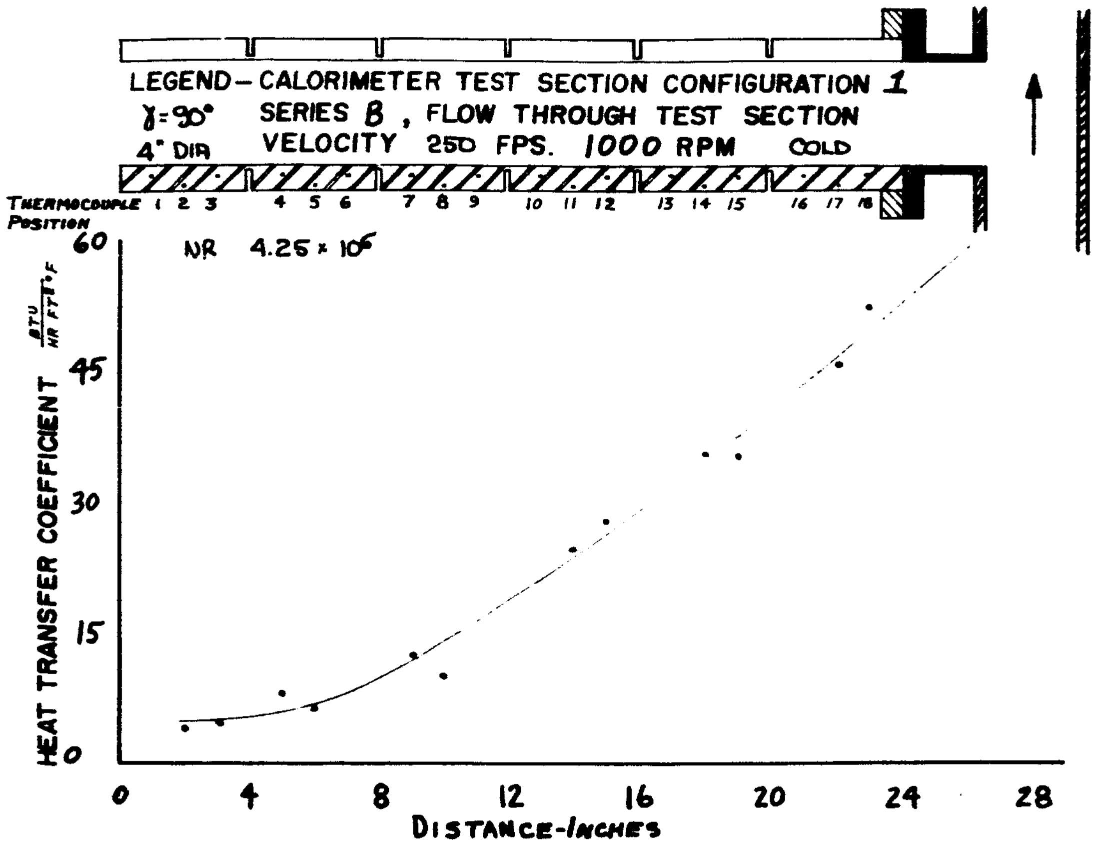


FIGURE A-41

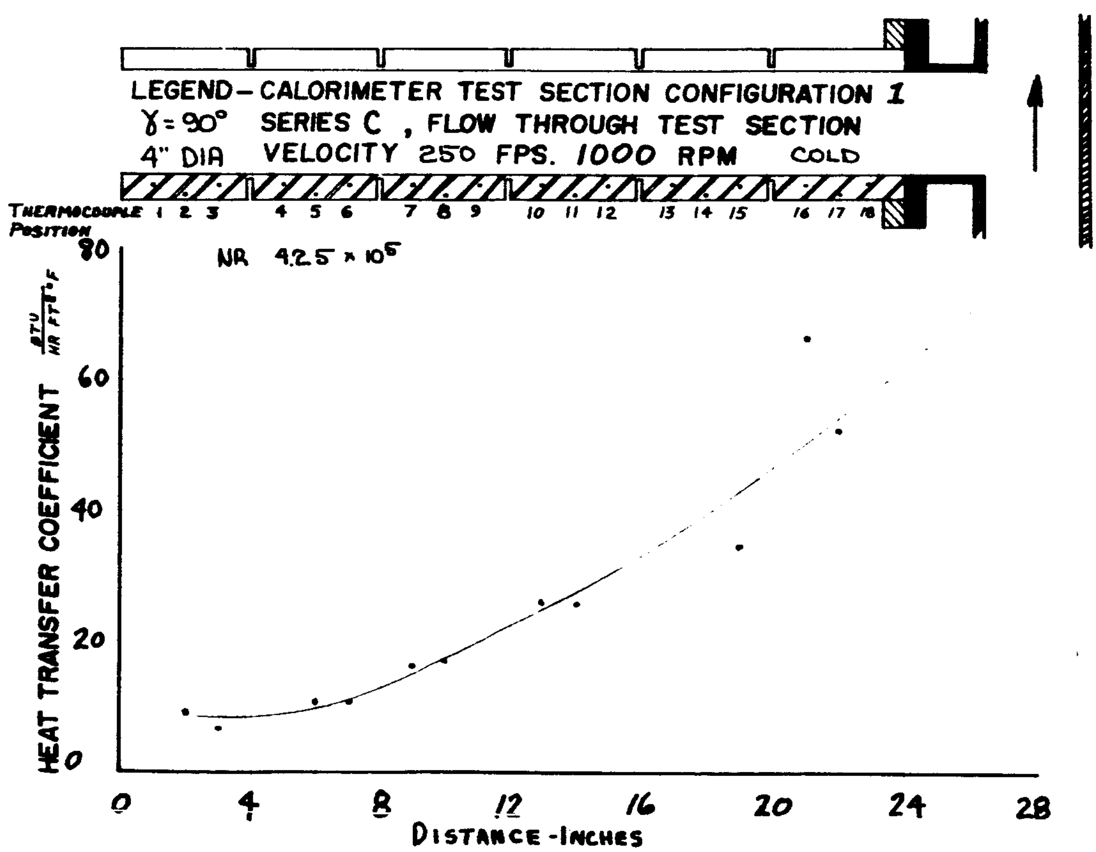


FIGURE A-42

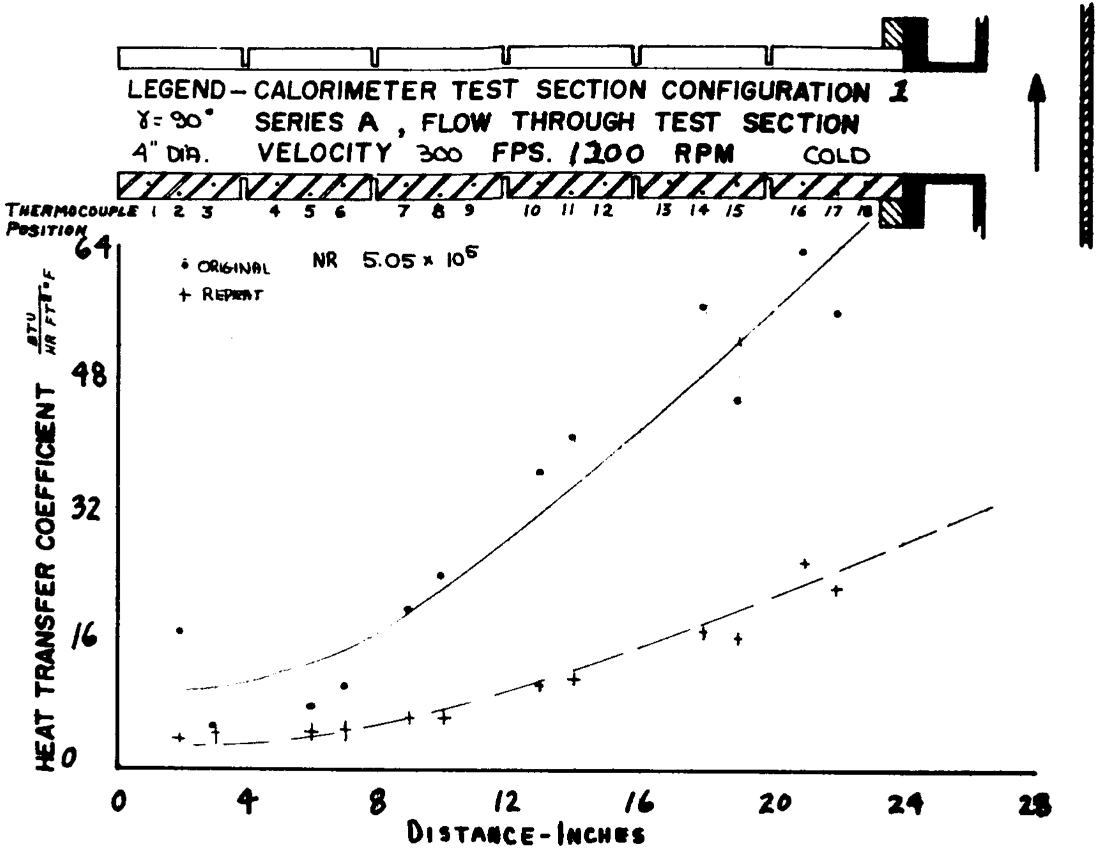


FIGURE A-43

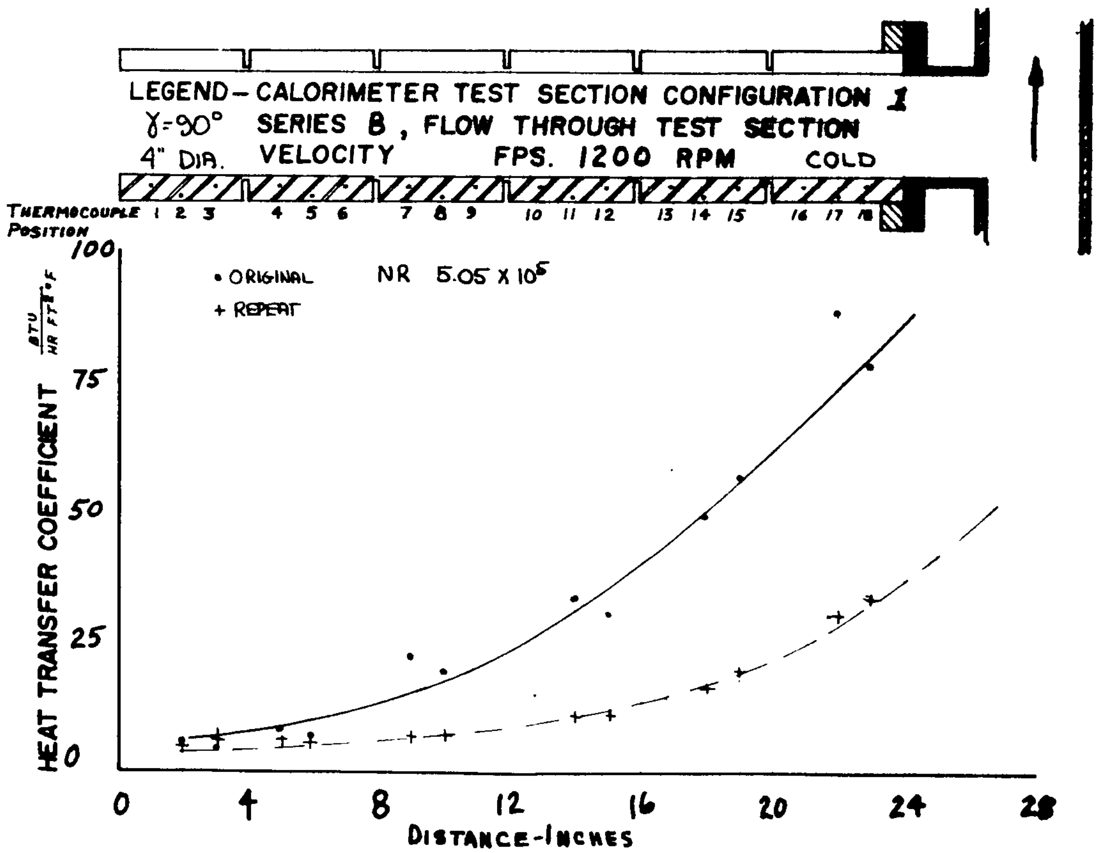


FIGURE A-44

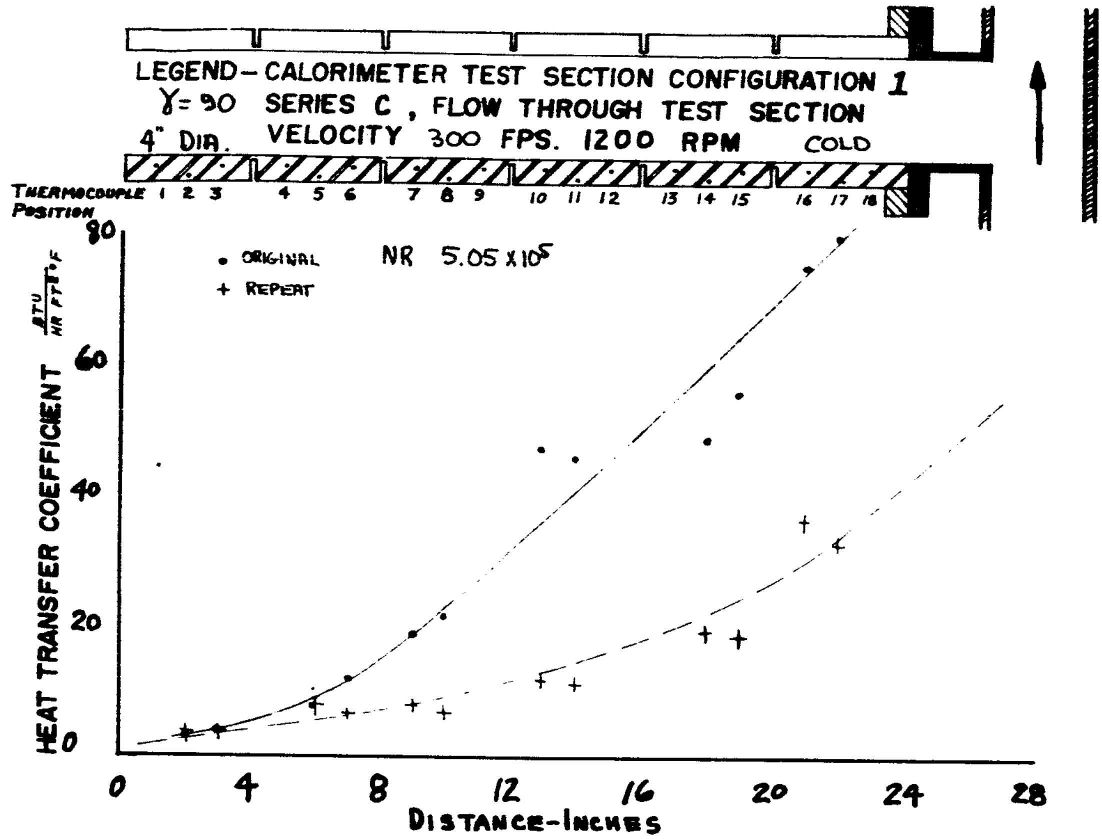


FIGURE A-45

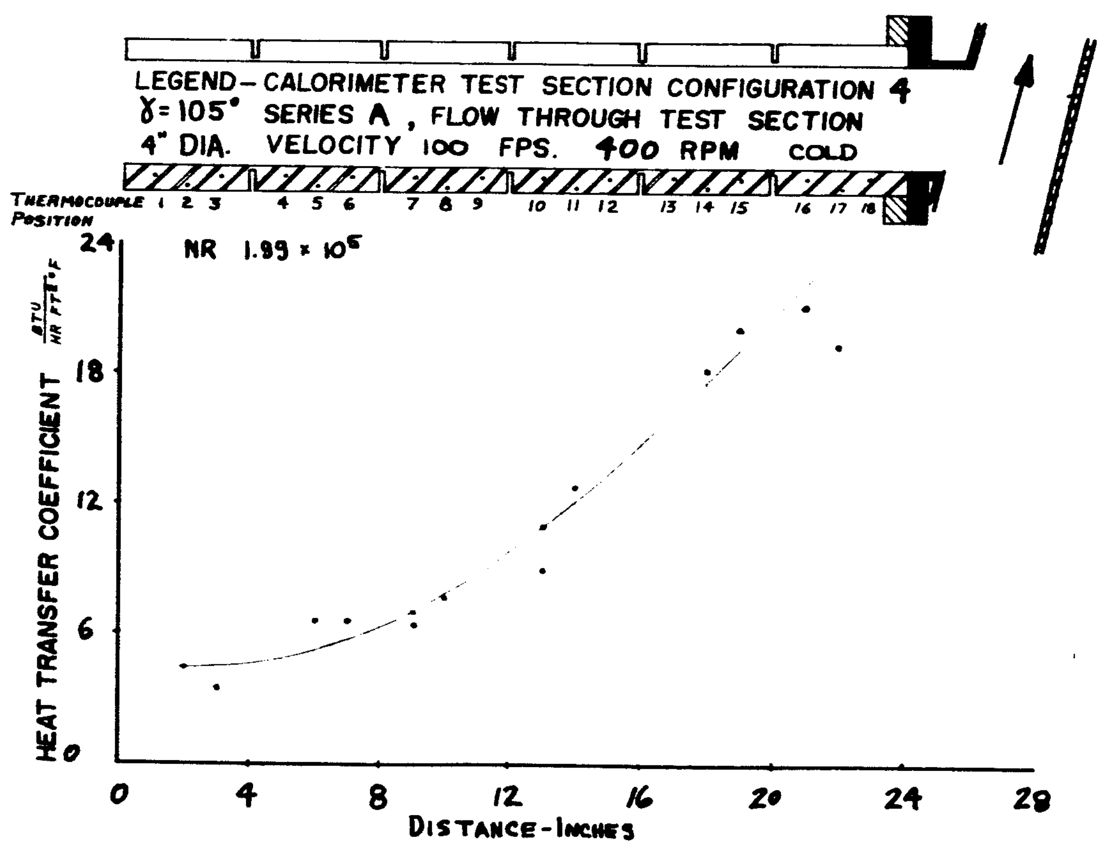


FIGURE A-46

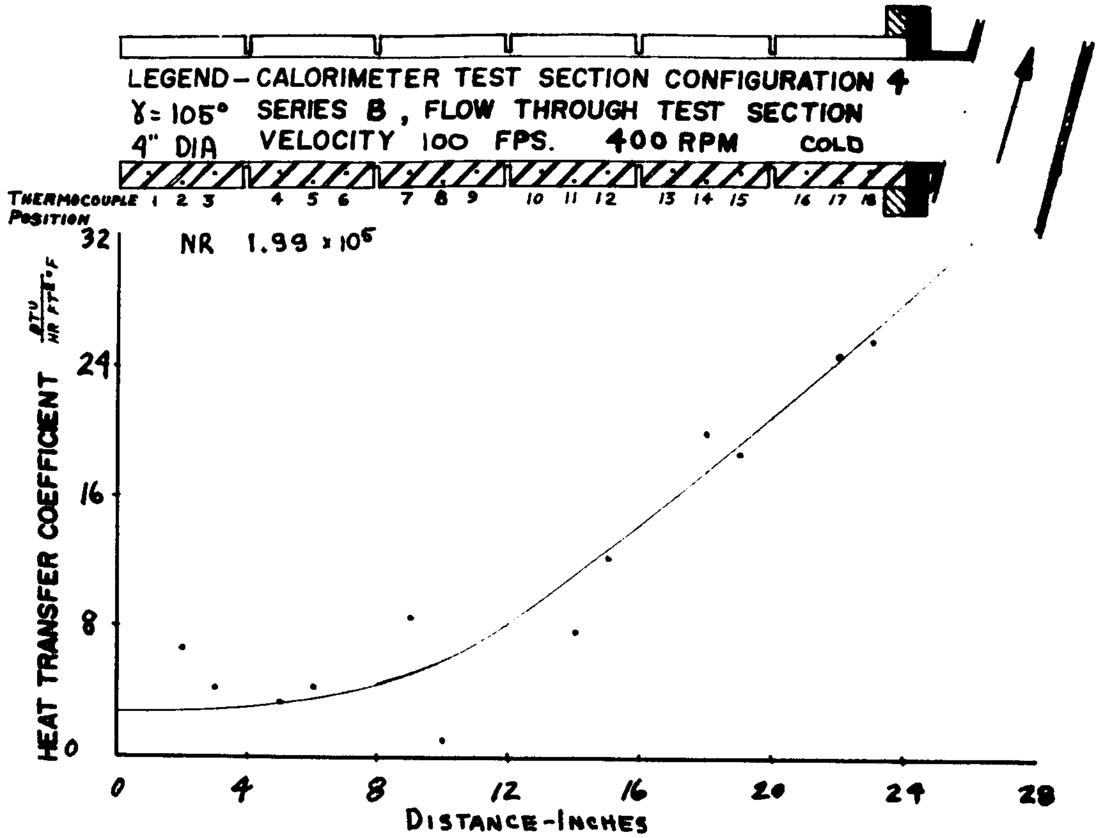


FIGURE A-47

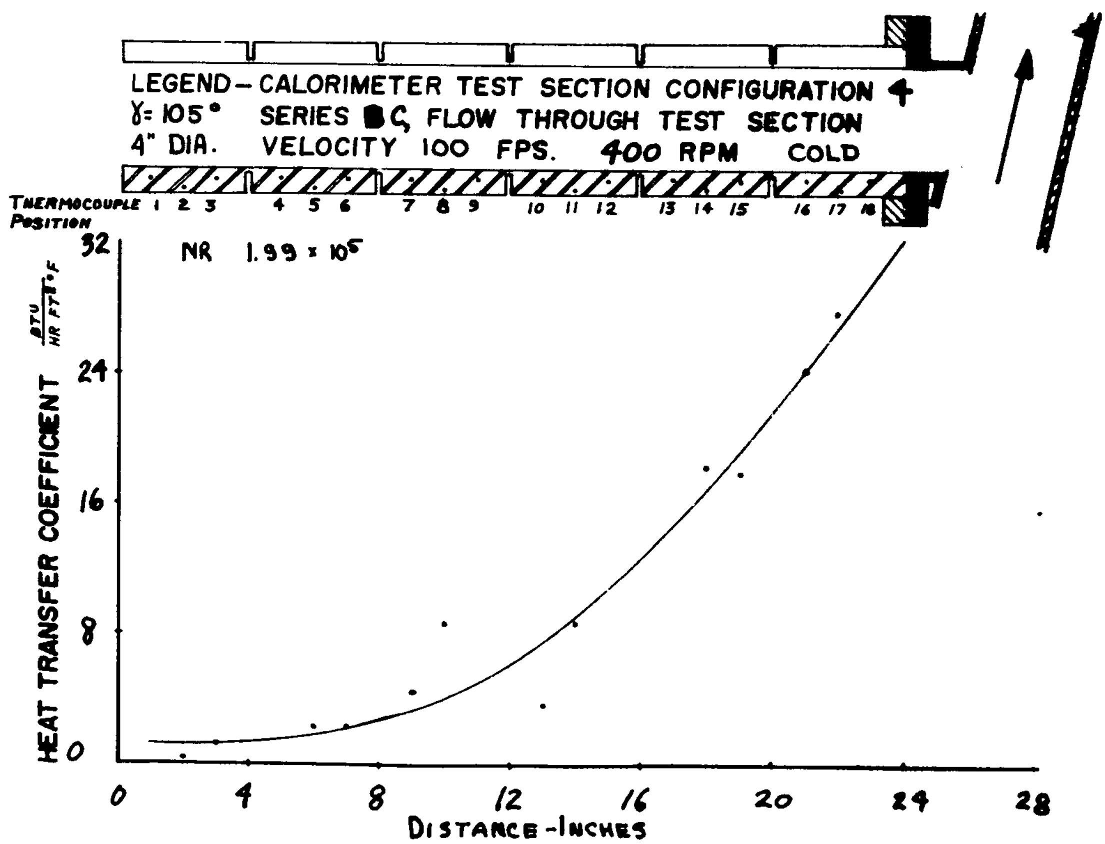


FIGURE A-48

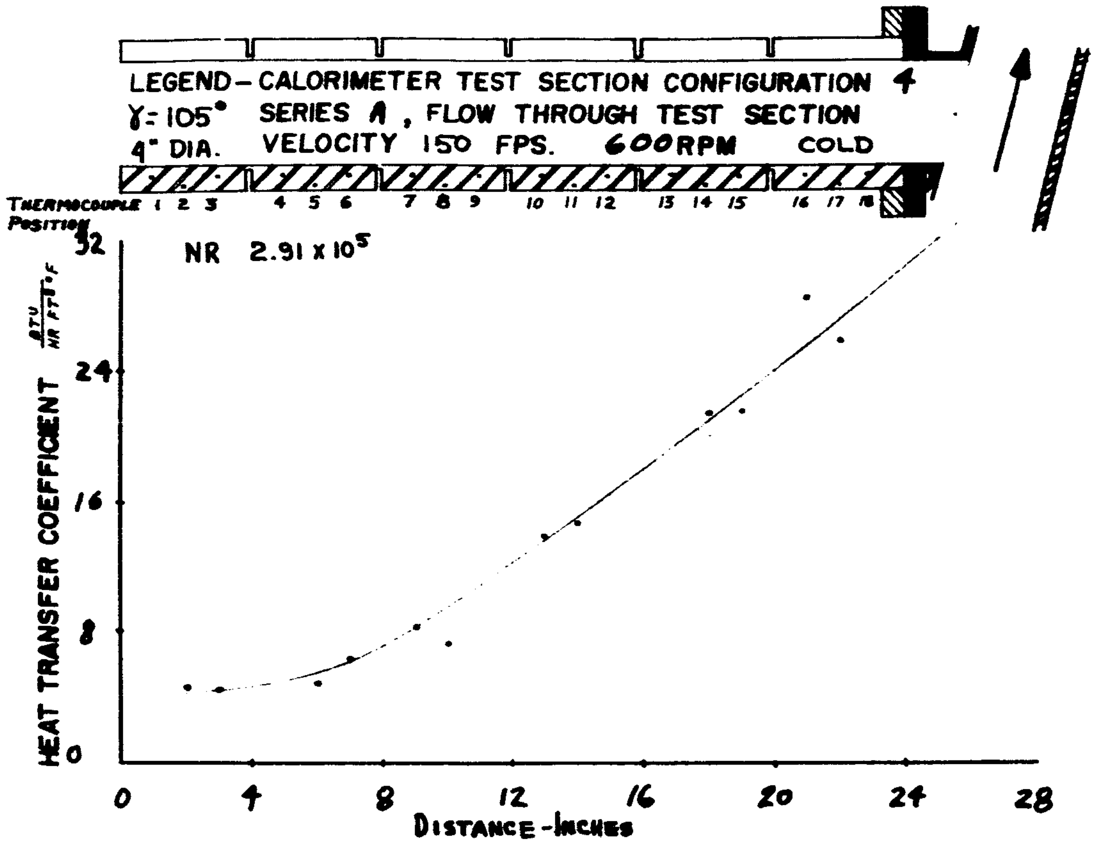


FIGURE A-49

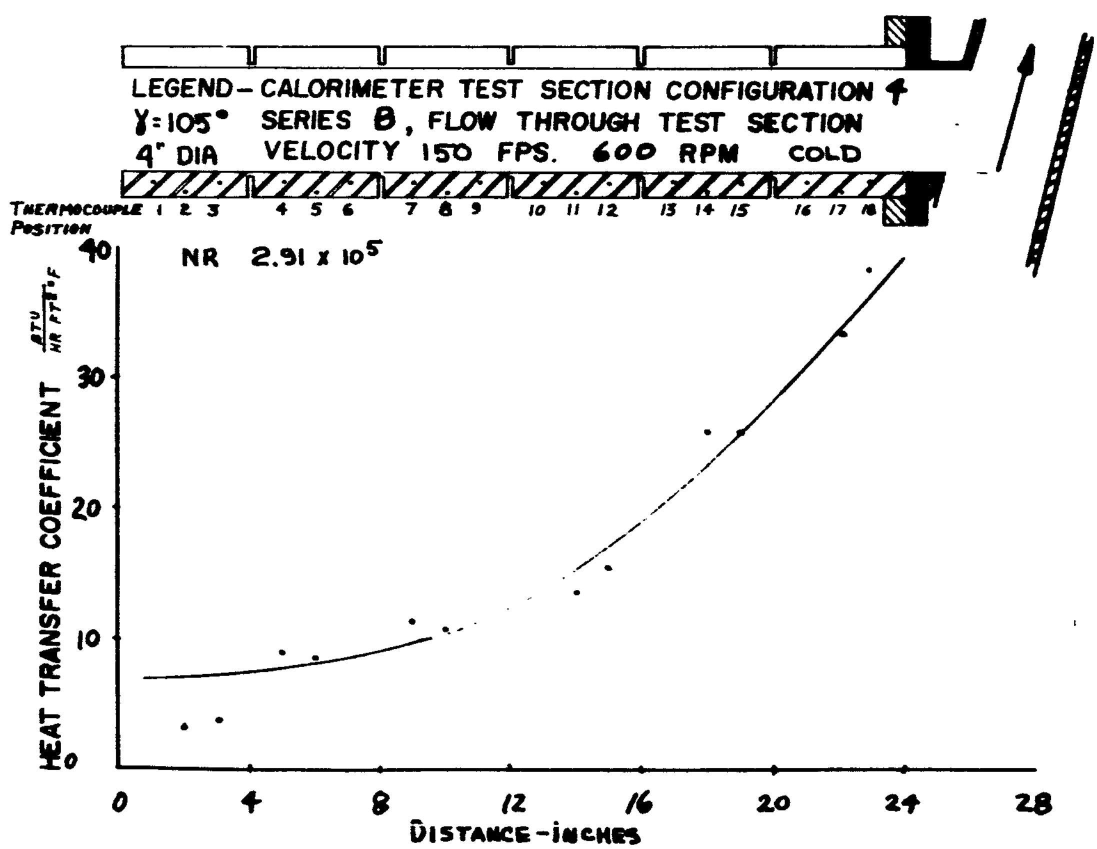


FIGURE A-50

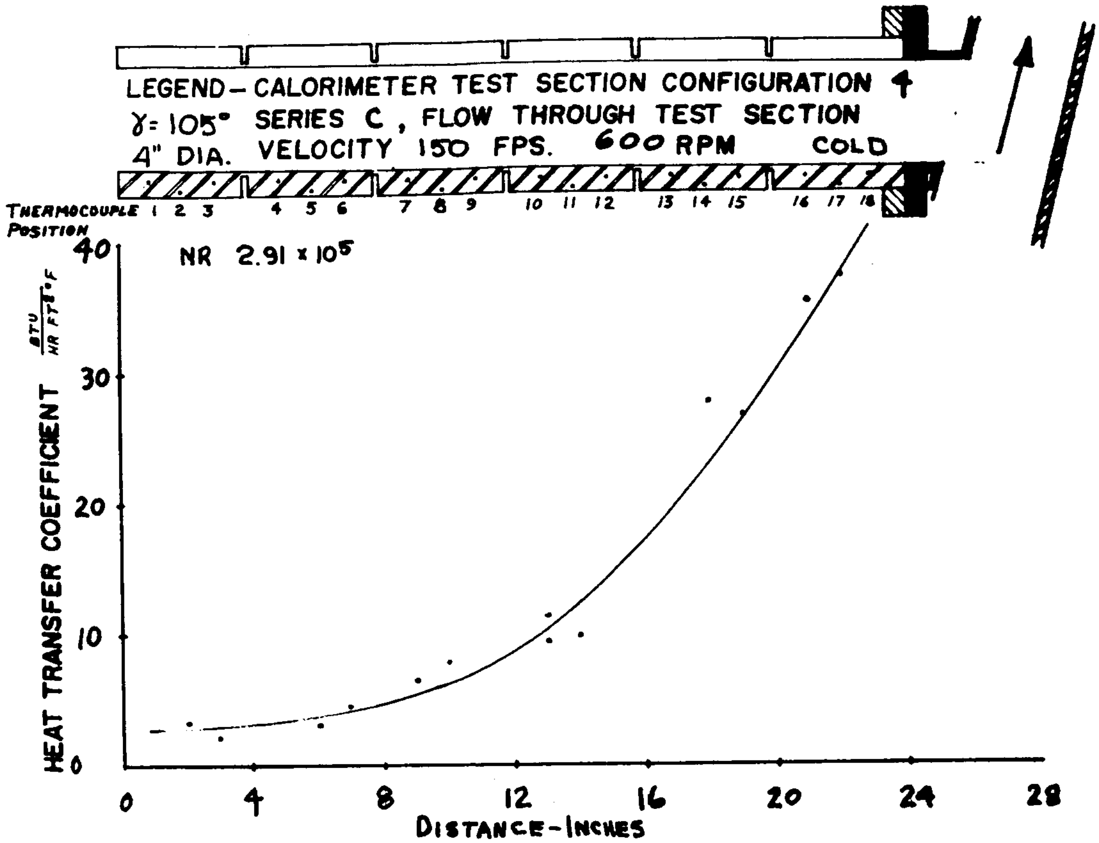


FIGURE A-51

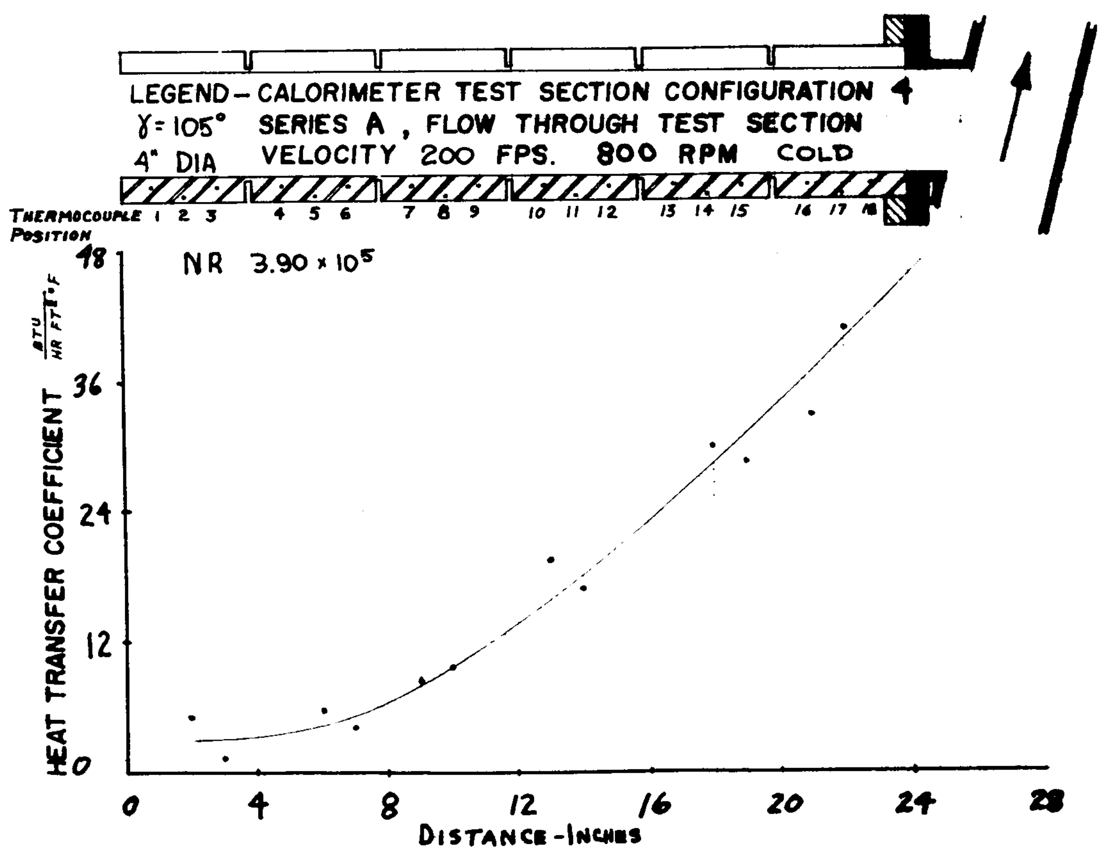


FIGURE A-52

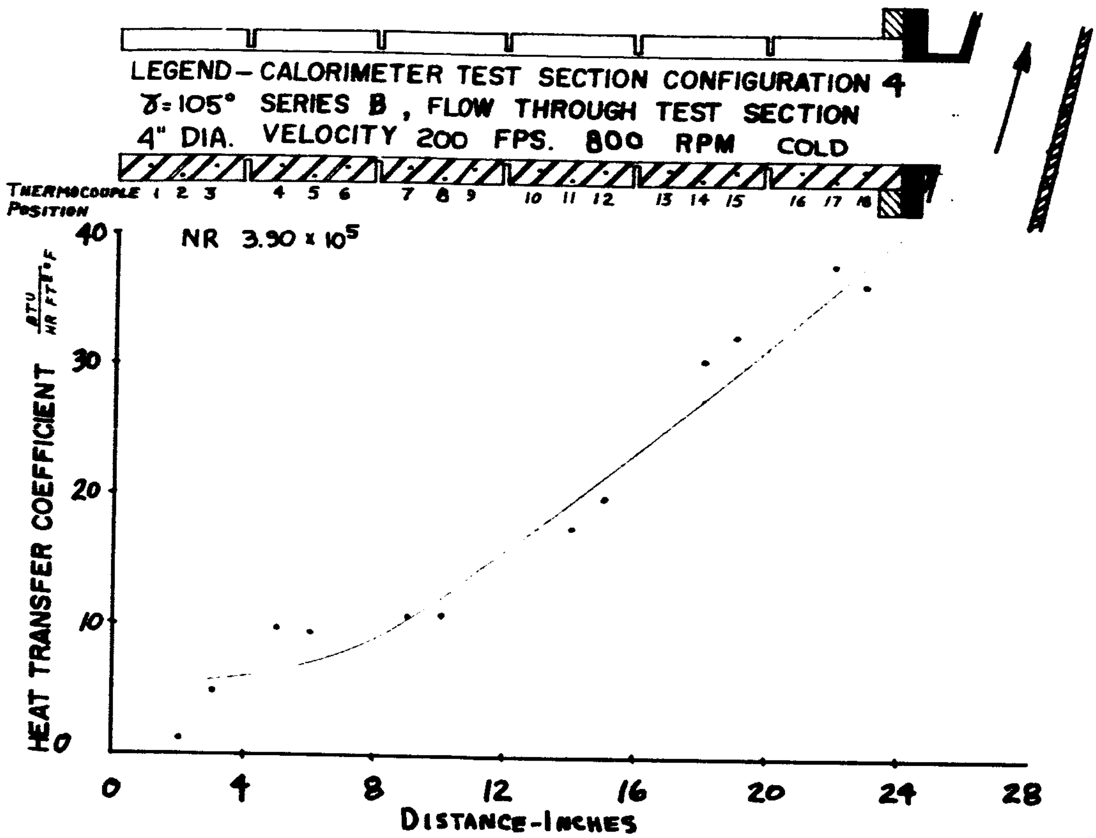


FIGURE A-53

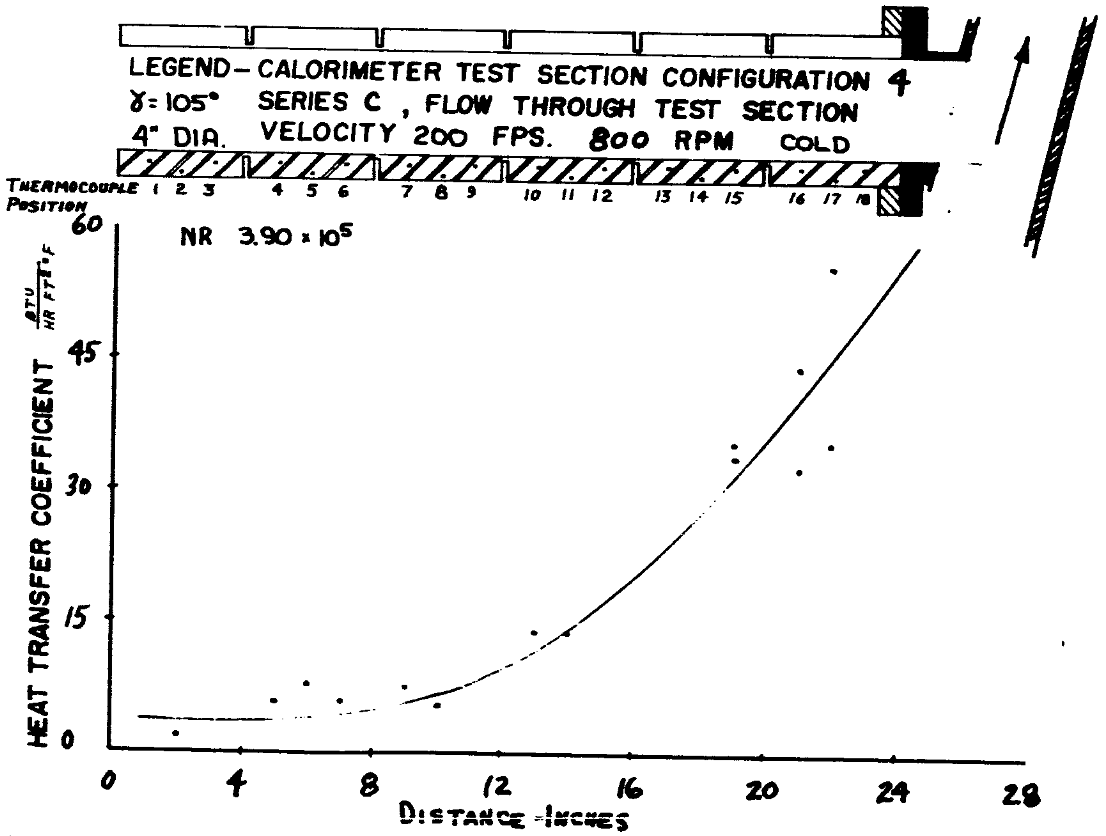


FIGURE A-54

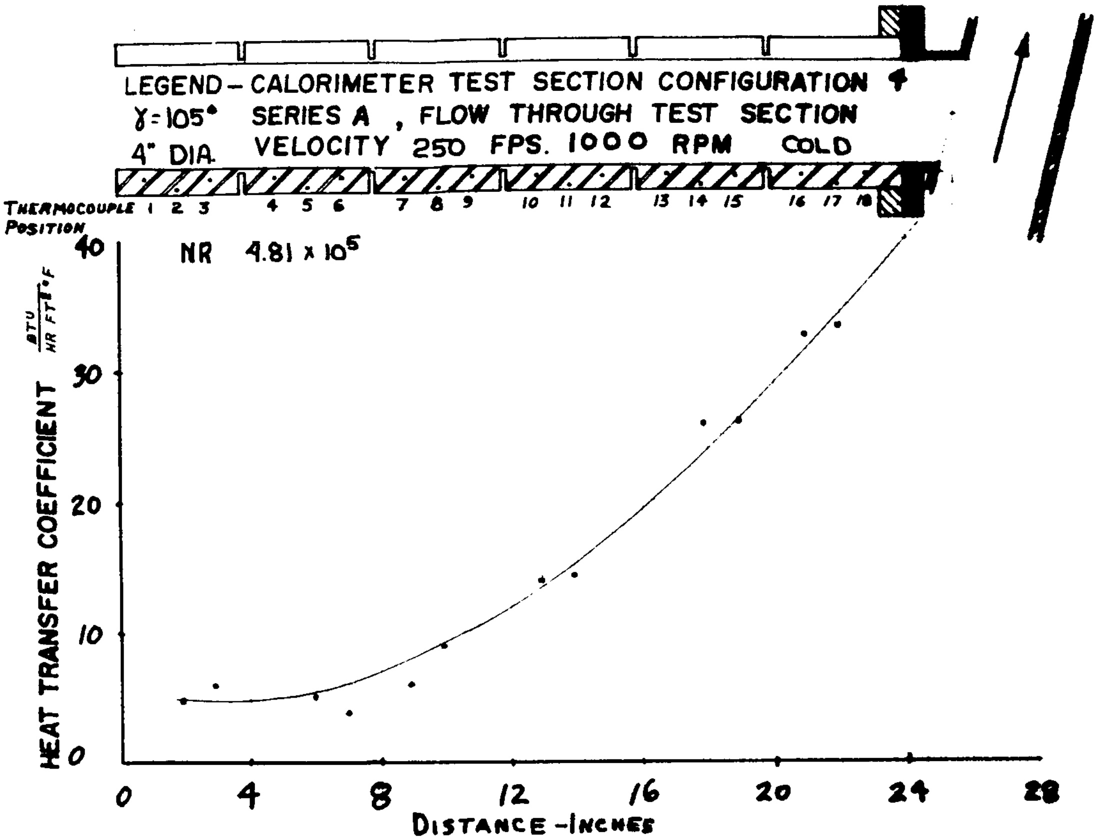


FIGURE A-55

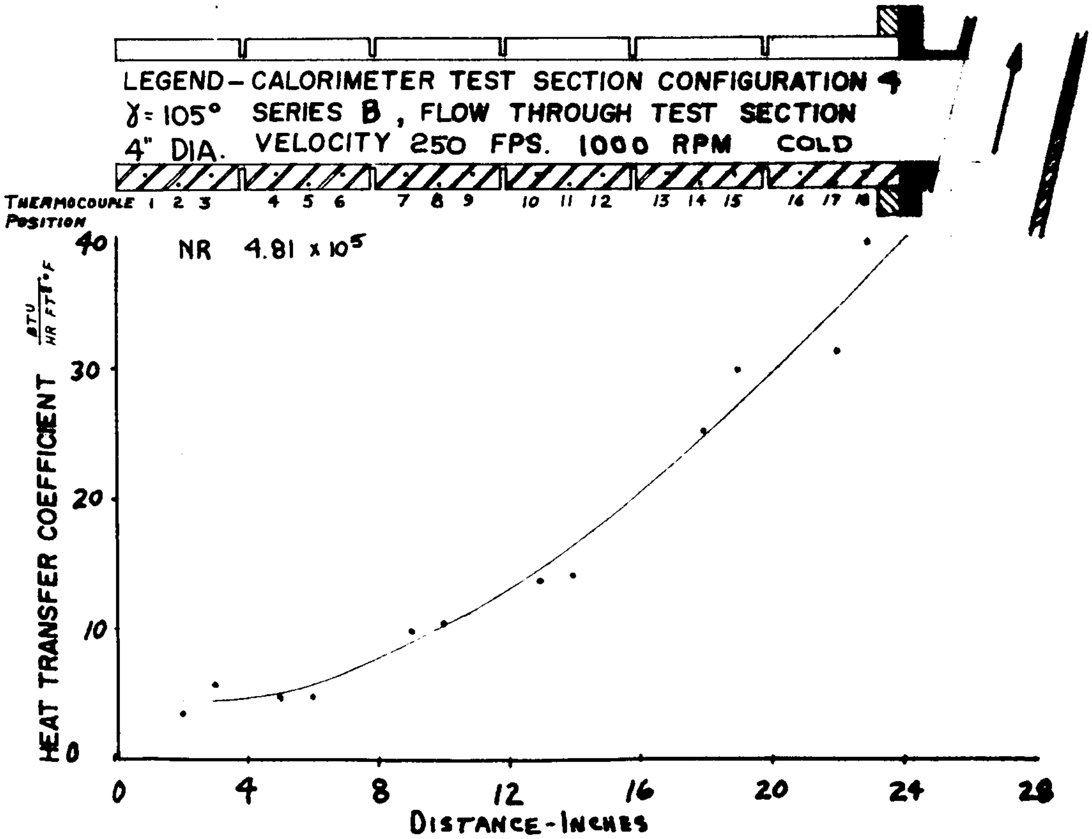


FIGURE A-56

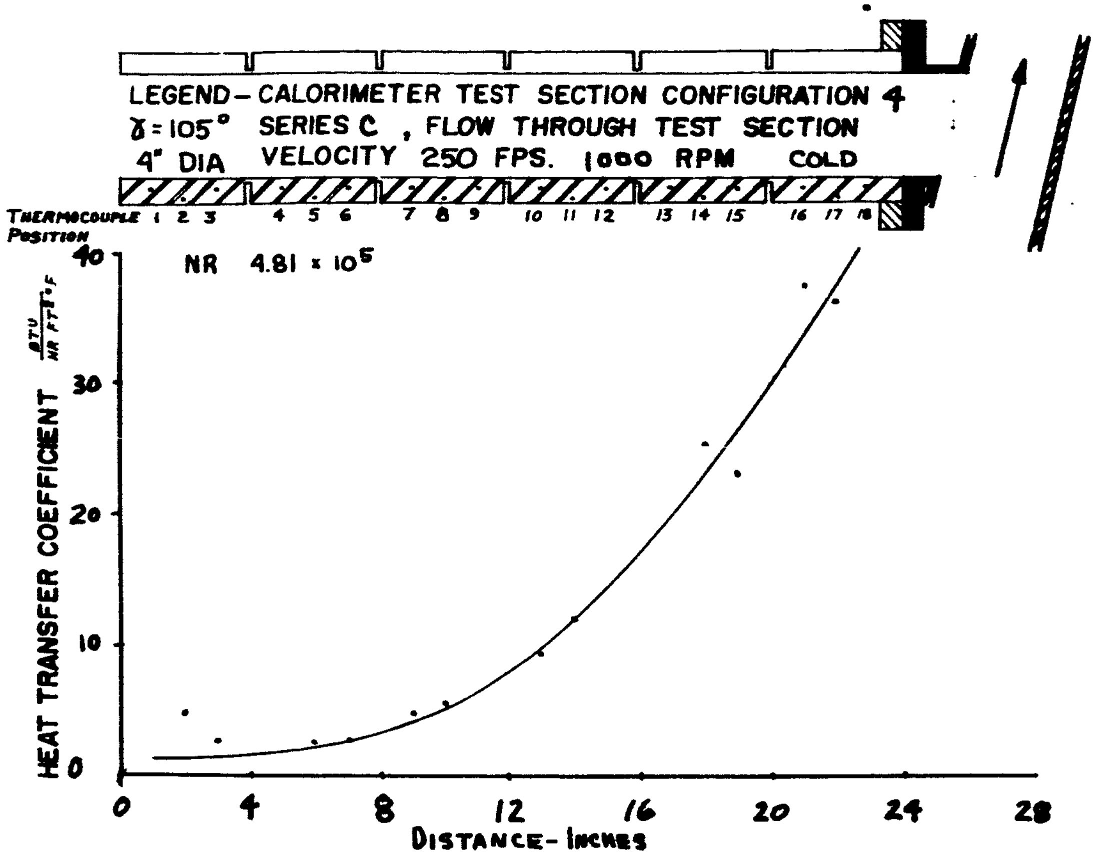


FIGURE A-57

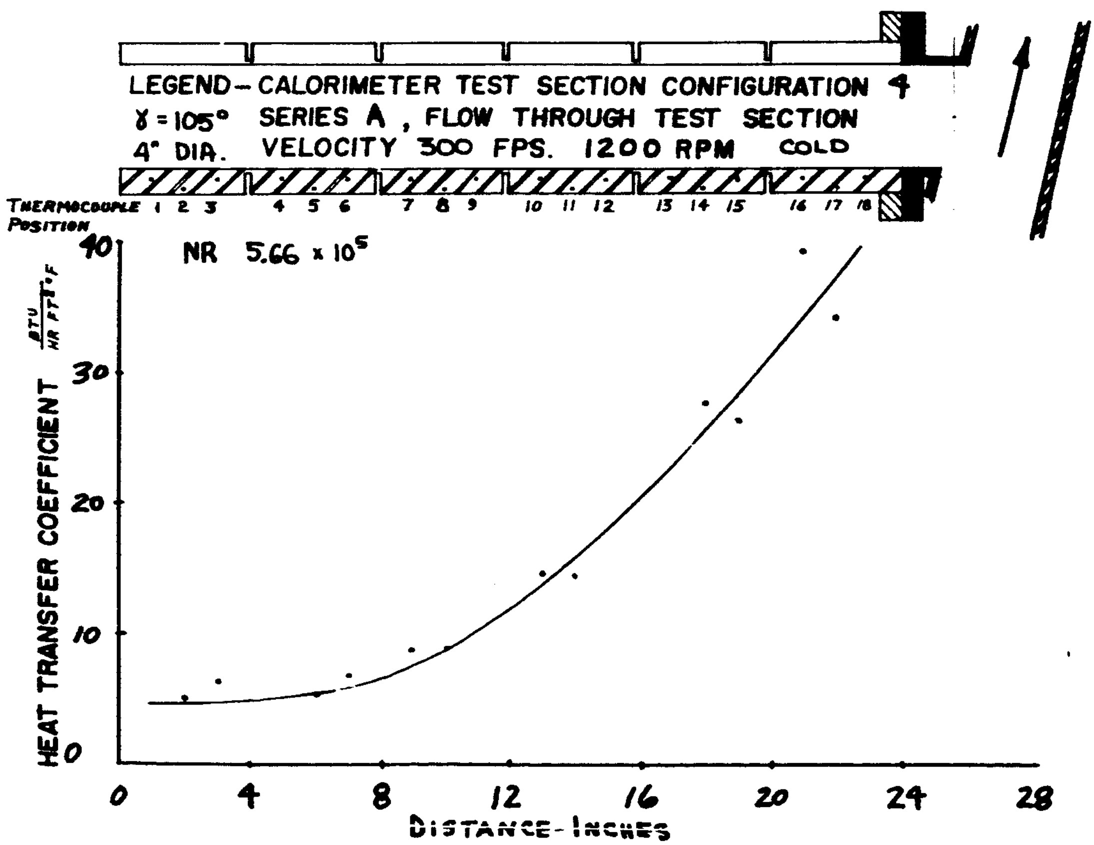


FIGURE A-58

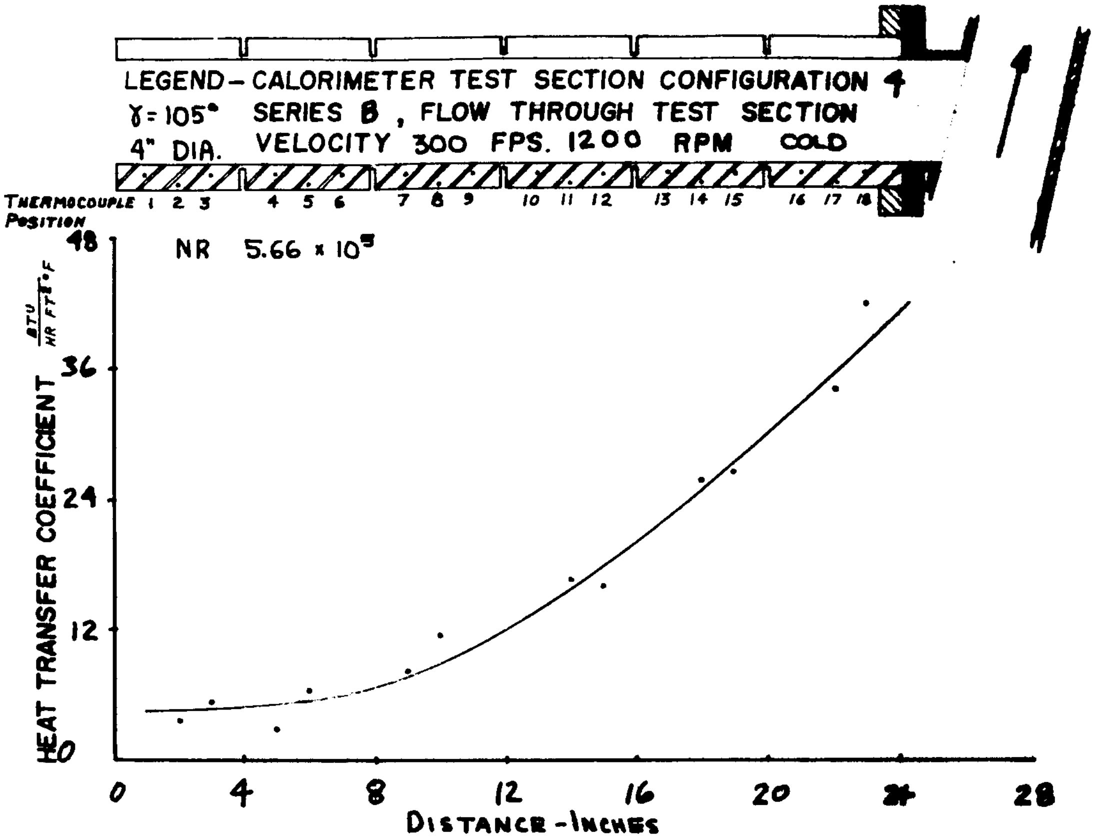


FIGURE A-59

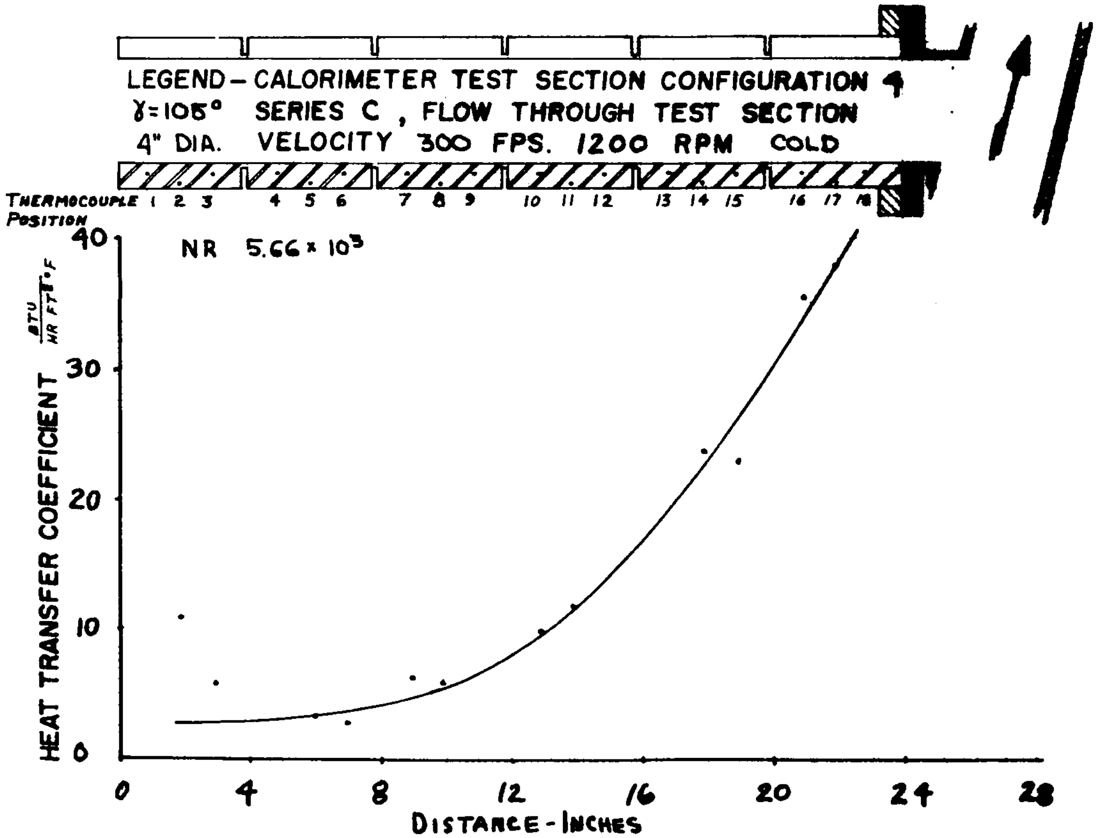


FIGURE A-60

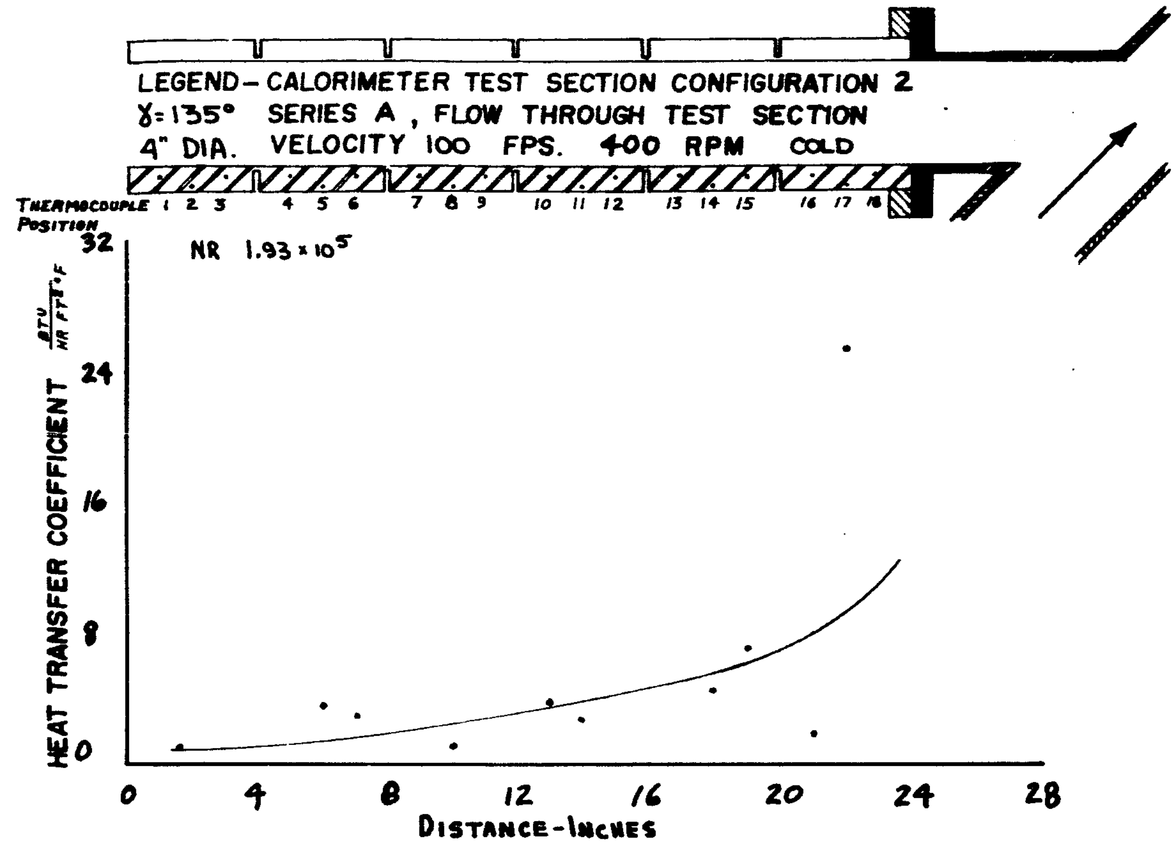


FIGURE A-61

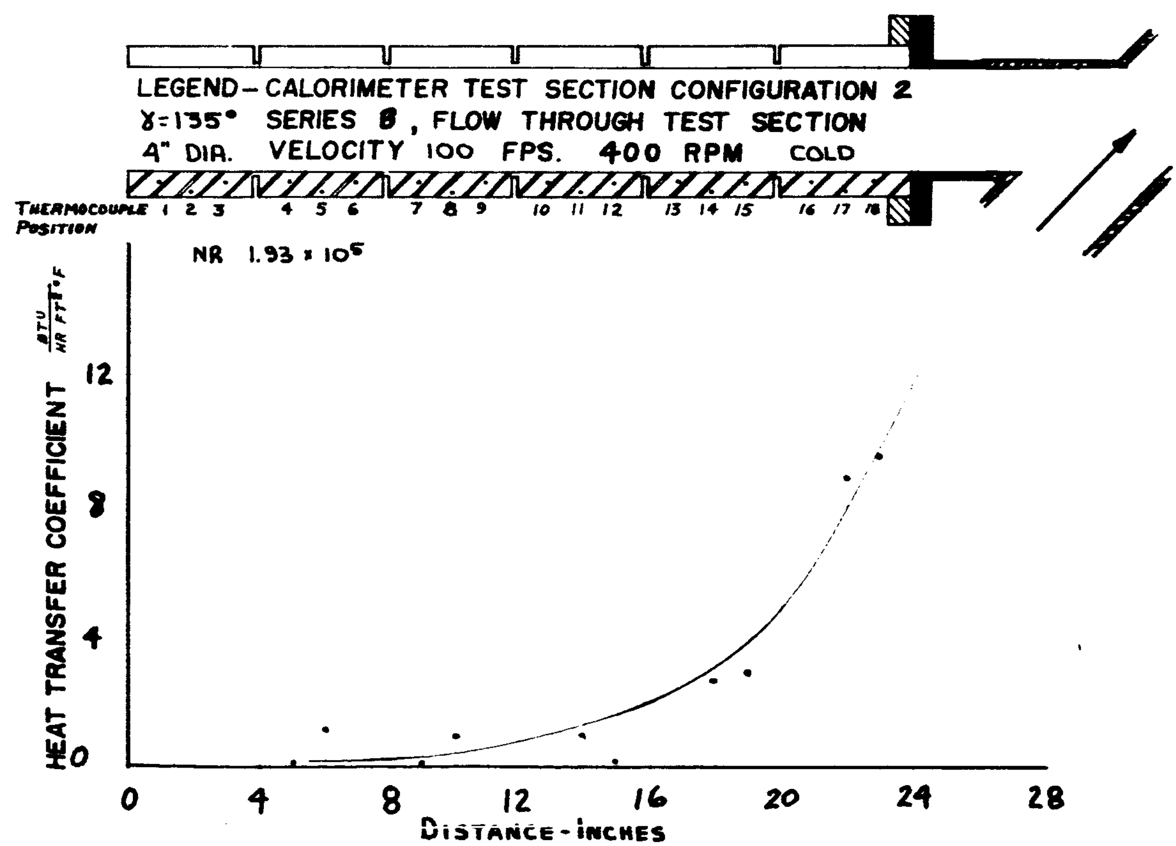


FIGURE A-62

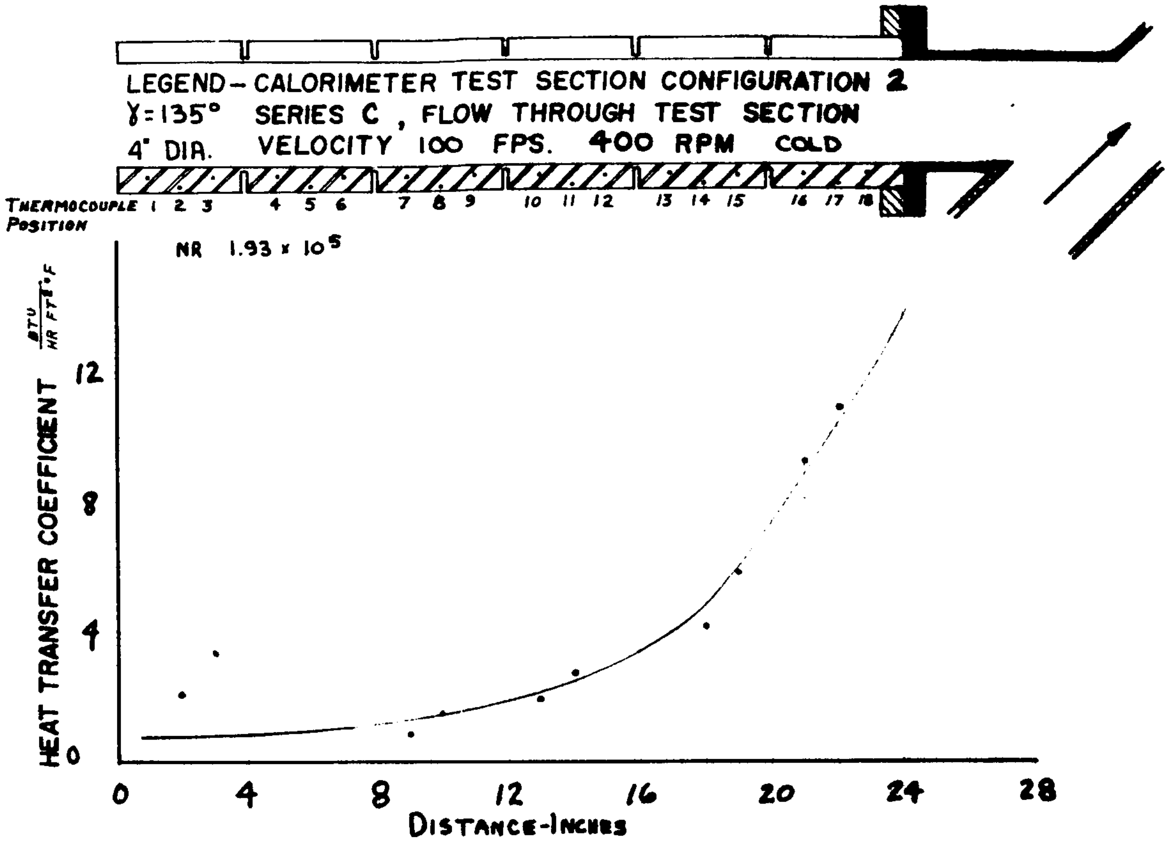


FIGURE A-63

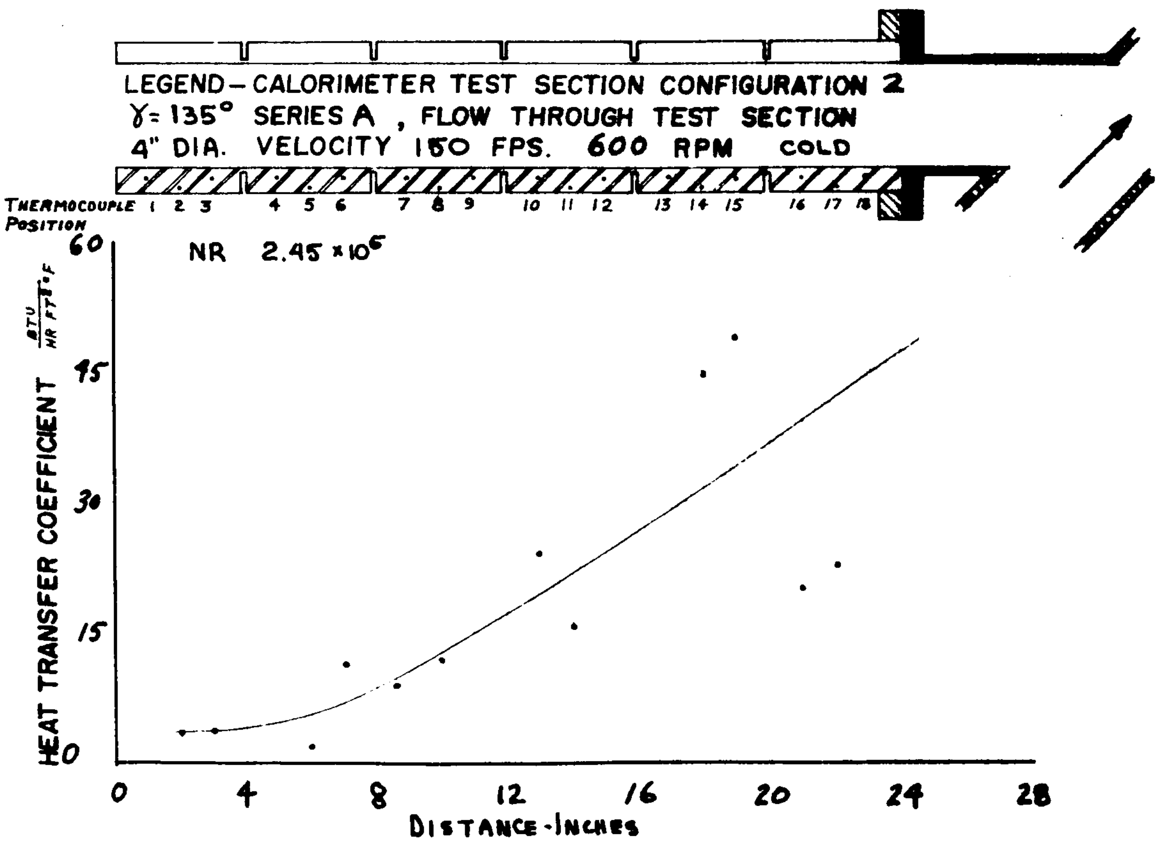


FIGURE A-64

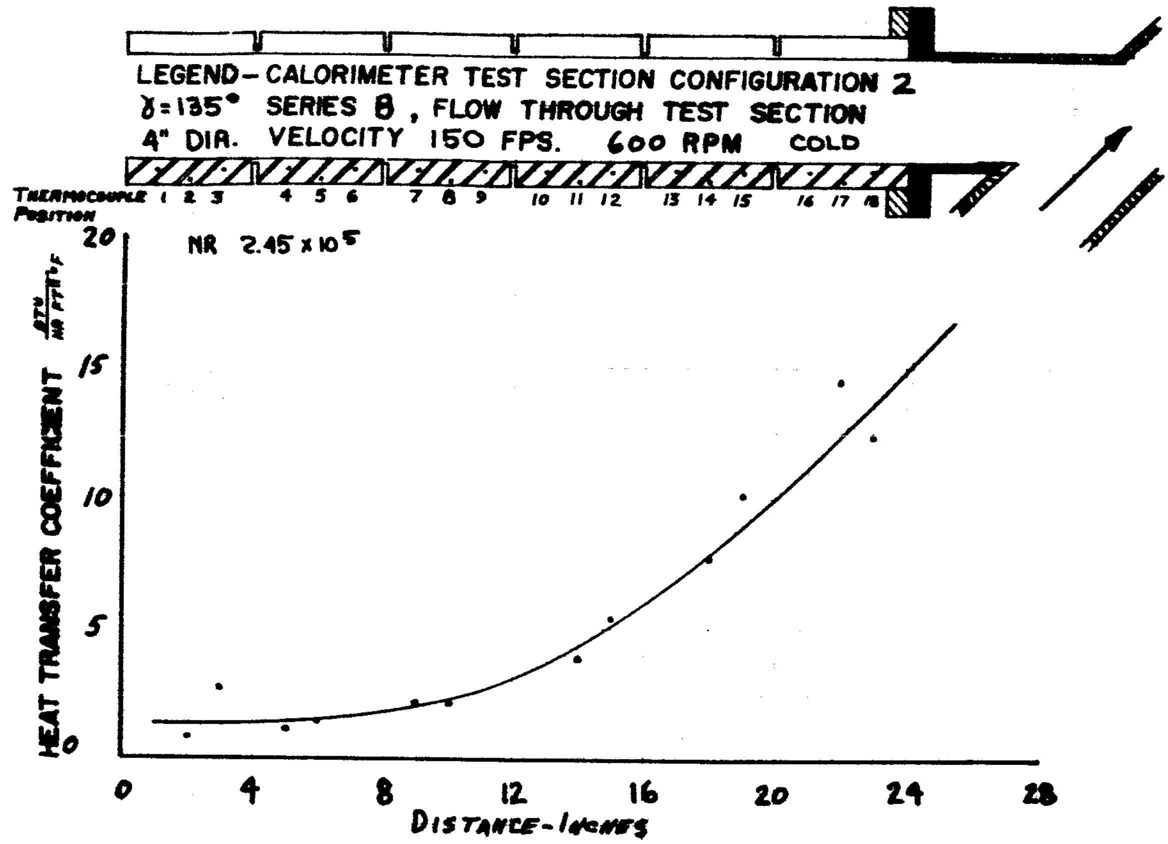


FIGURE A-65

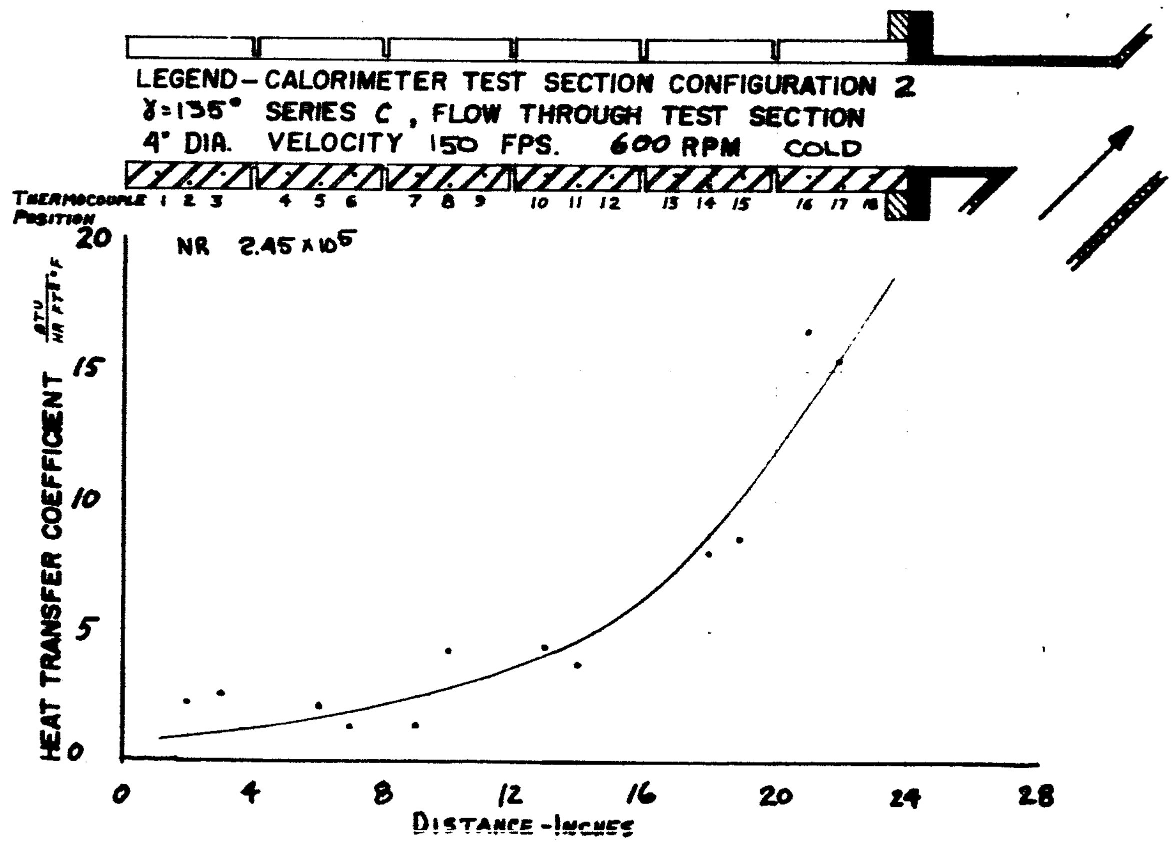


FIGURE A-66

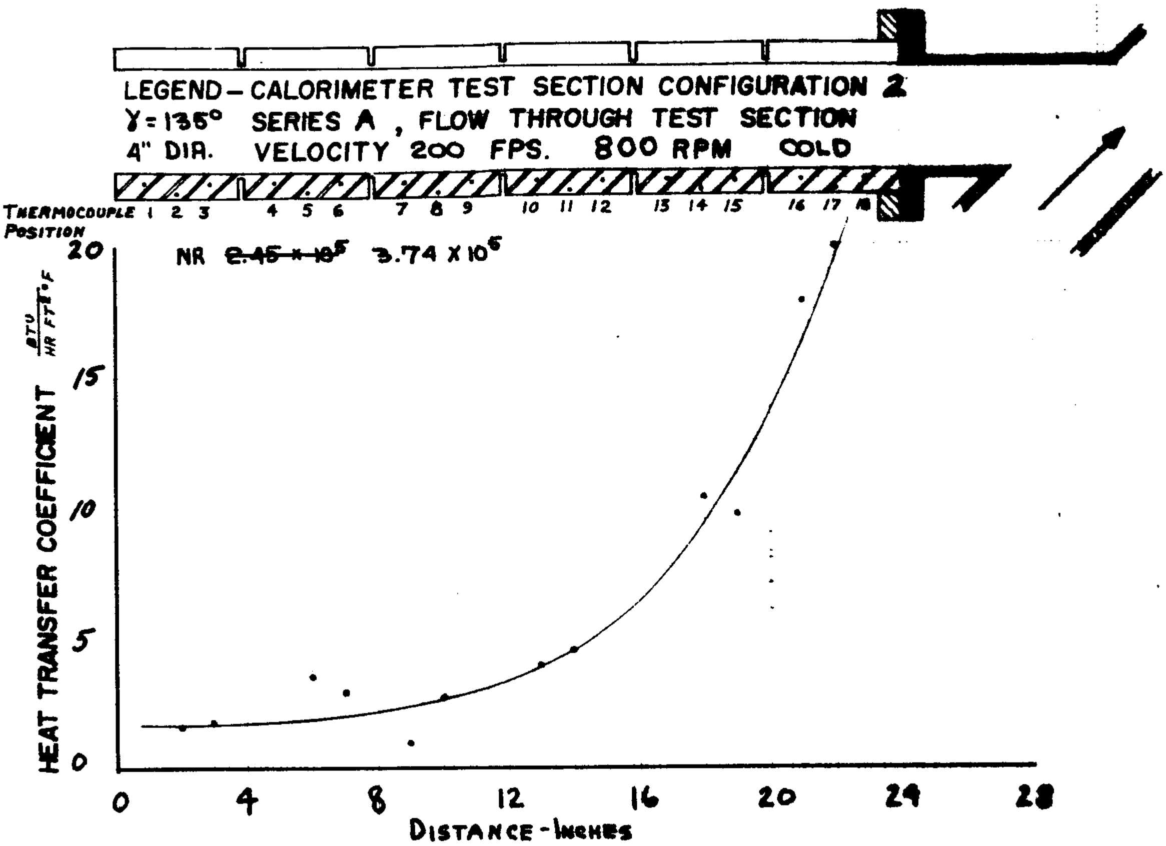


FIGURE A-67

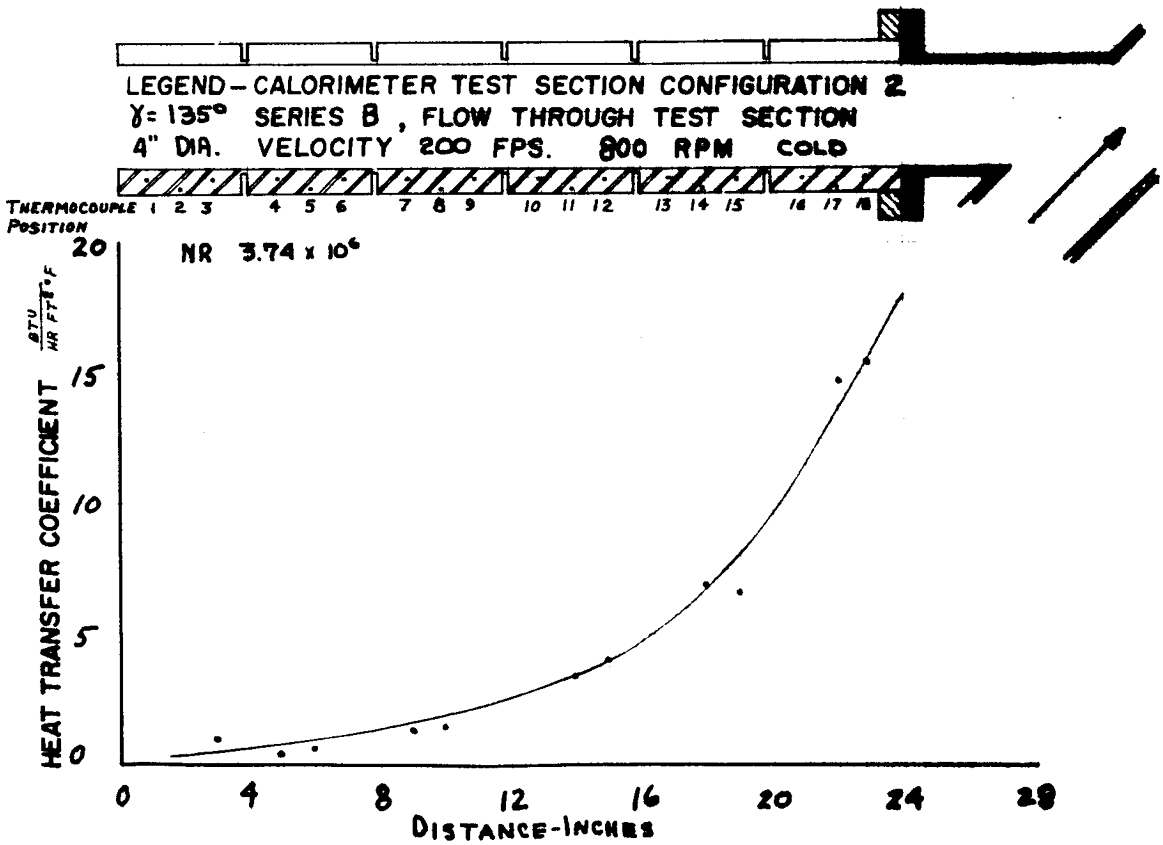


FIGURE A-68

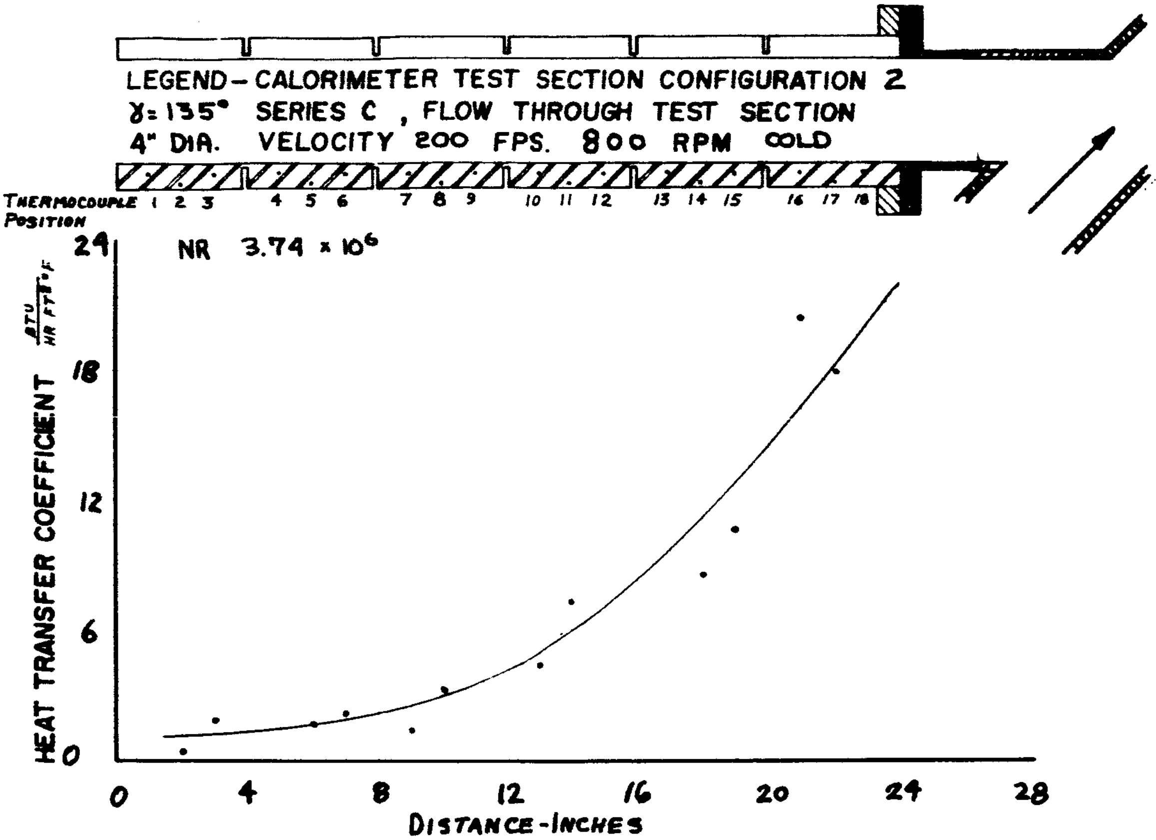


FIGURE A-69

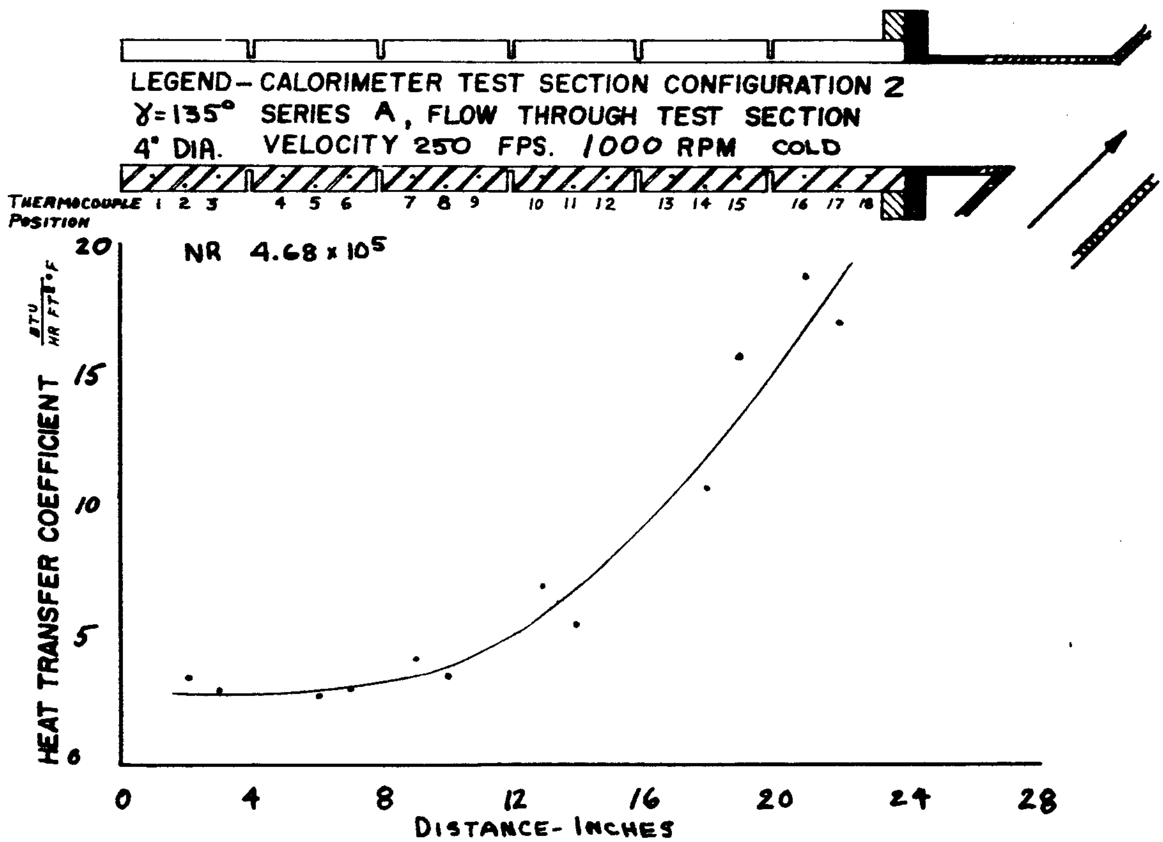


FIGURE A-70

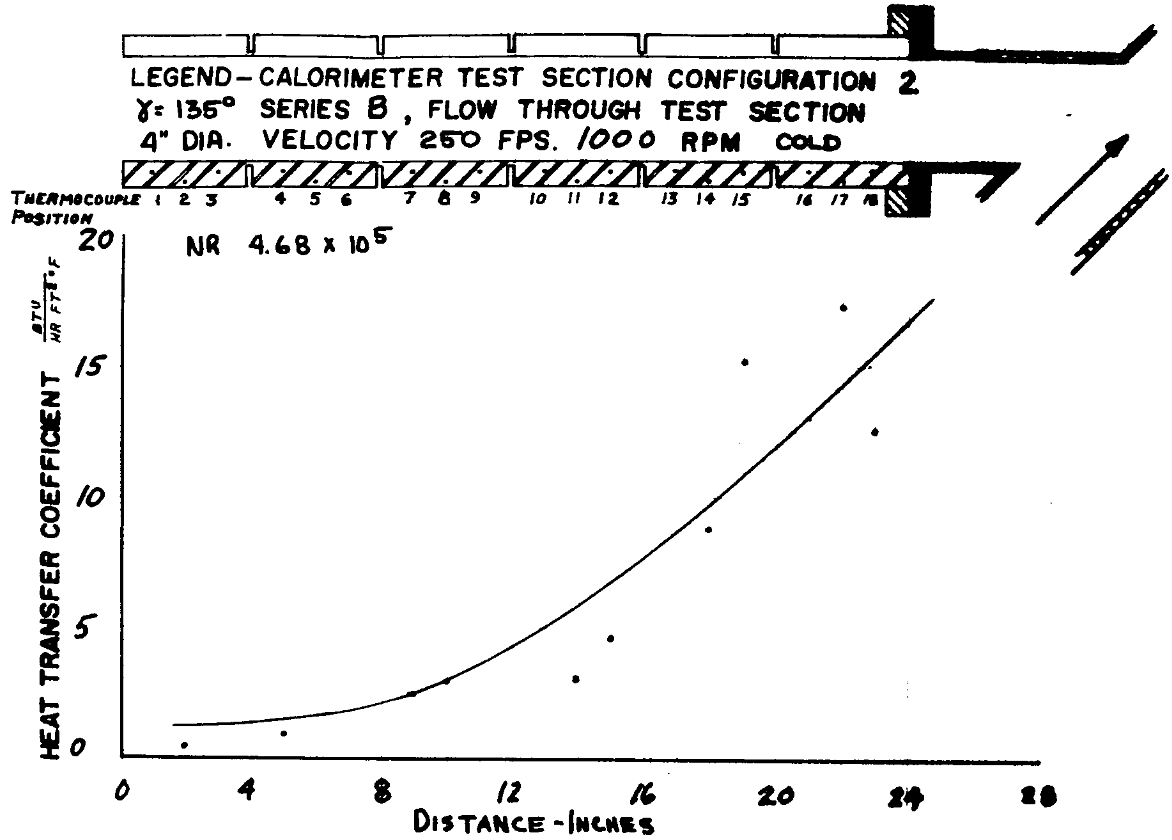


FIGURE A-71

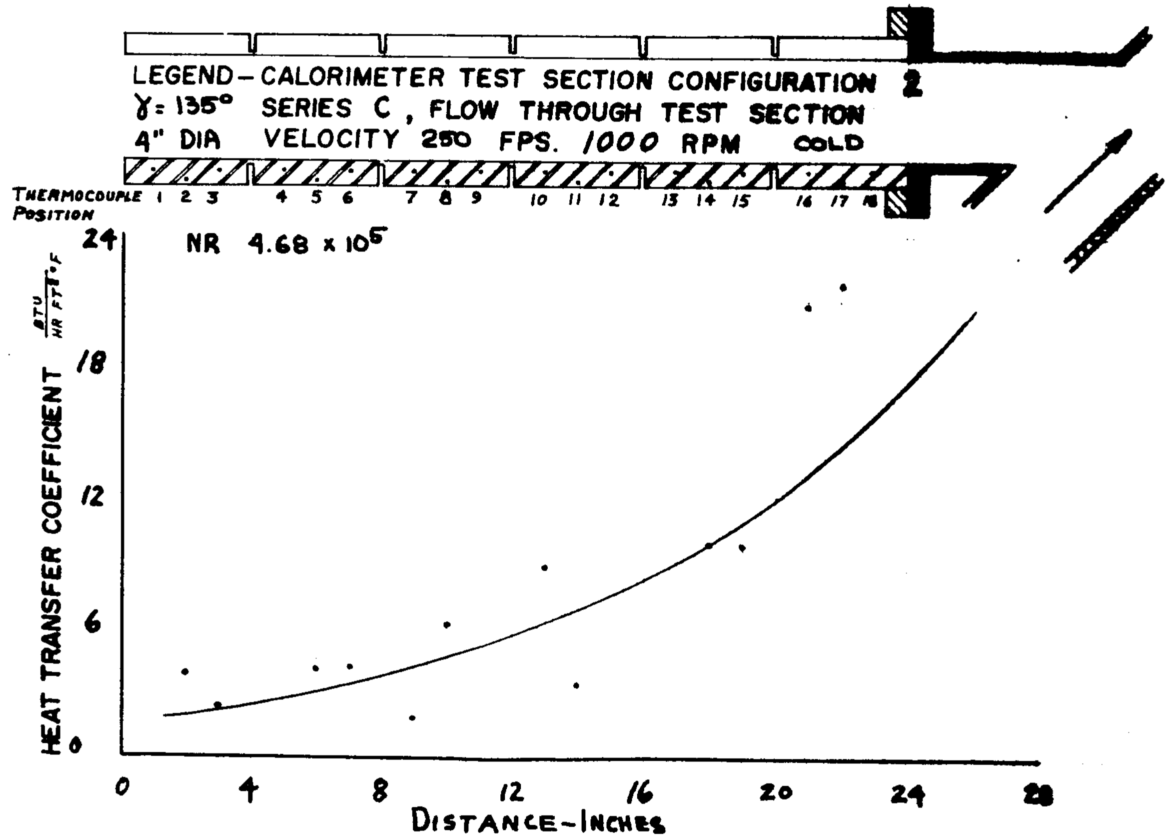


FIGURE A-72

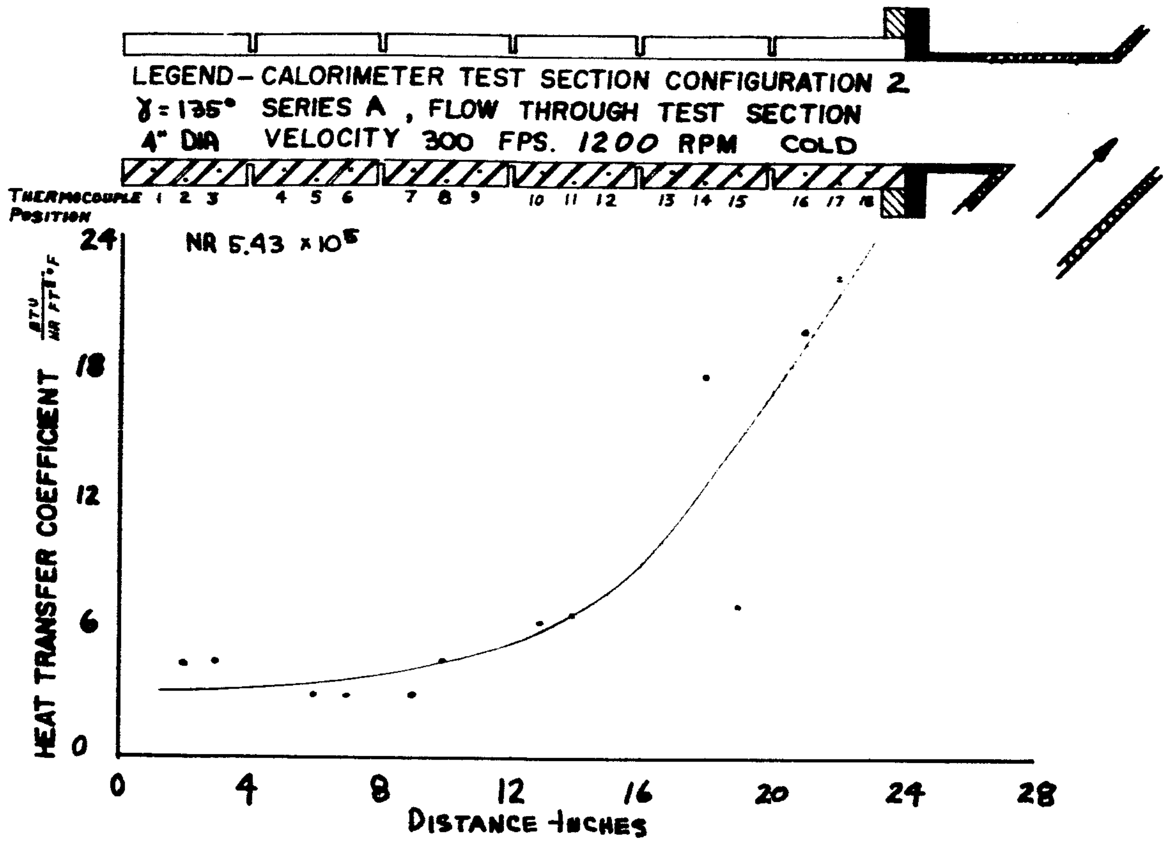


FIGURE A-73

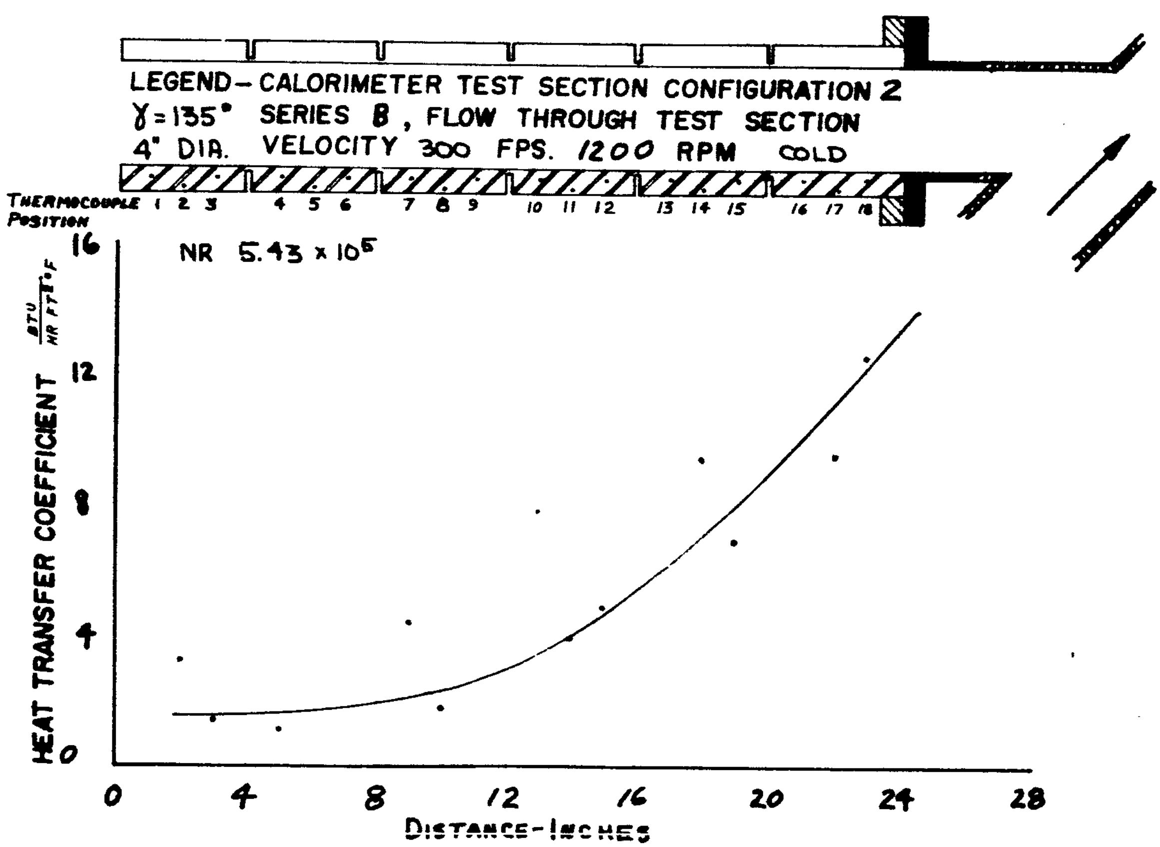


FIGURE A-74

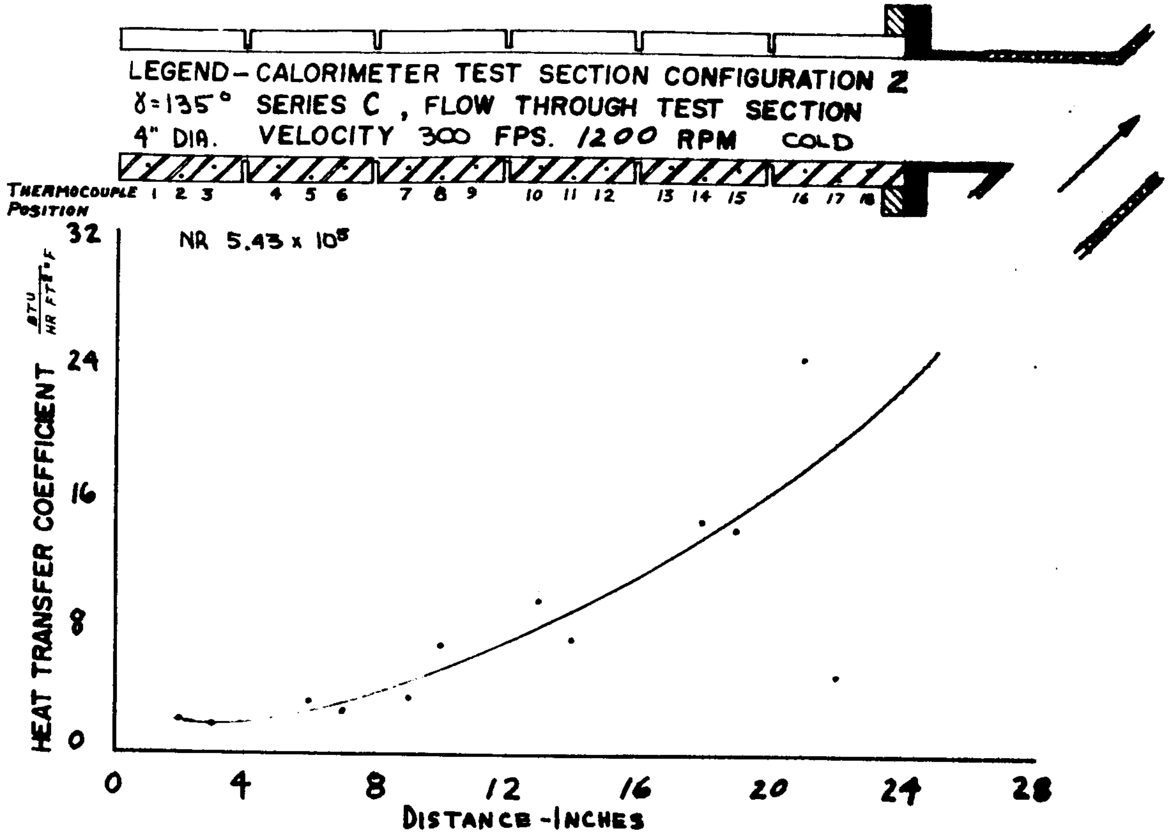


FIGURE A-75

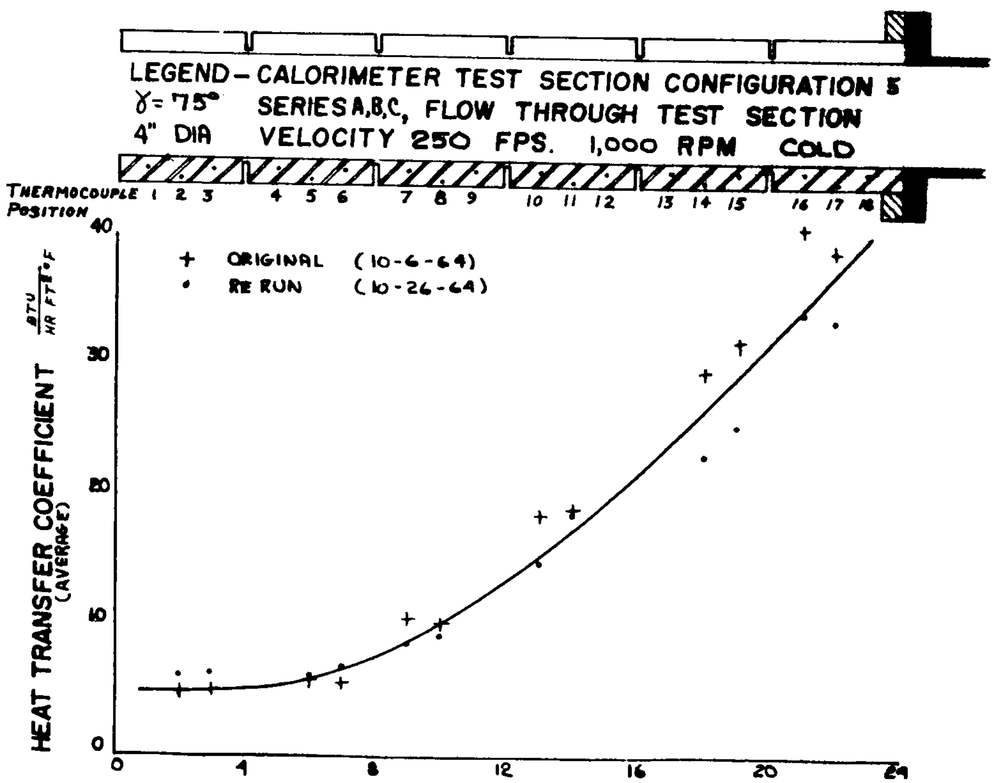


FIGURE A-76

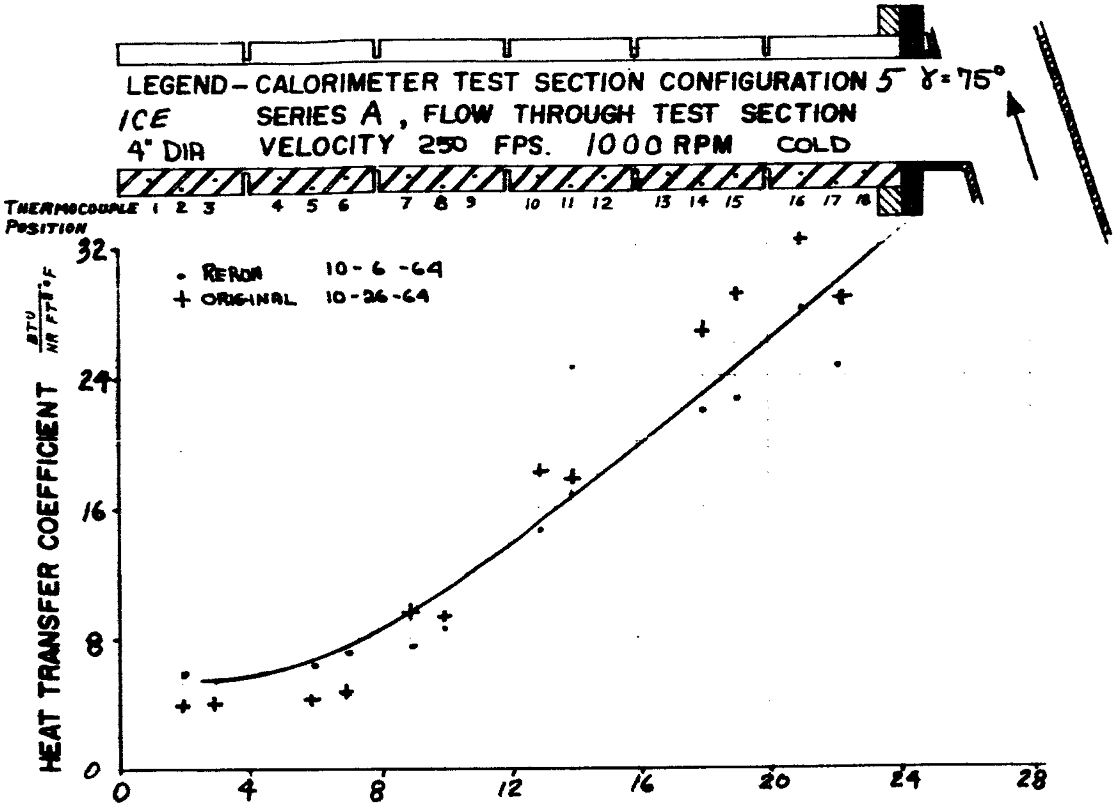


FIGURE A-77

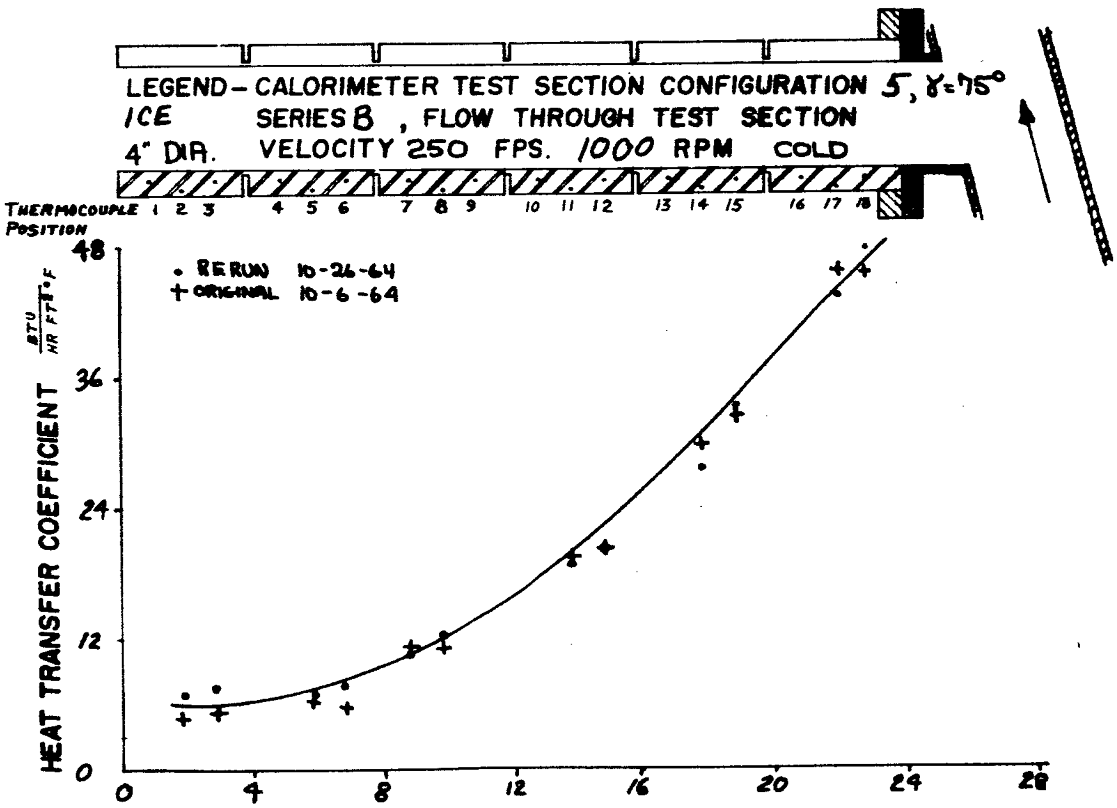


FIGURE A-78

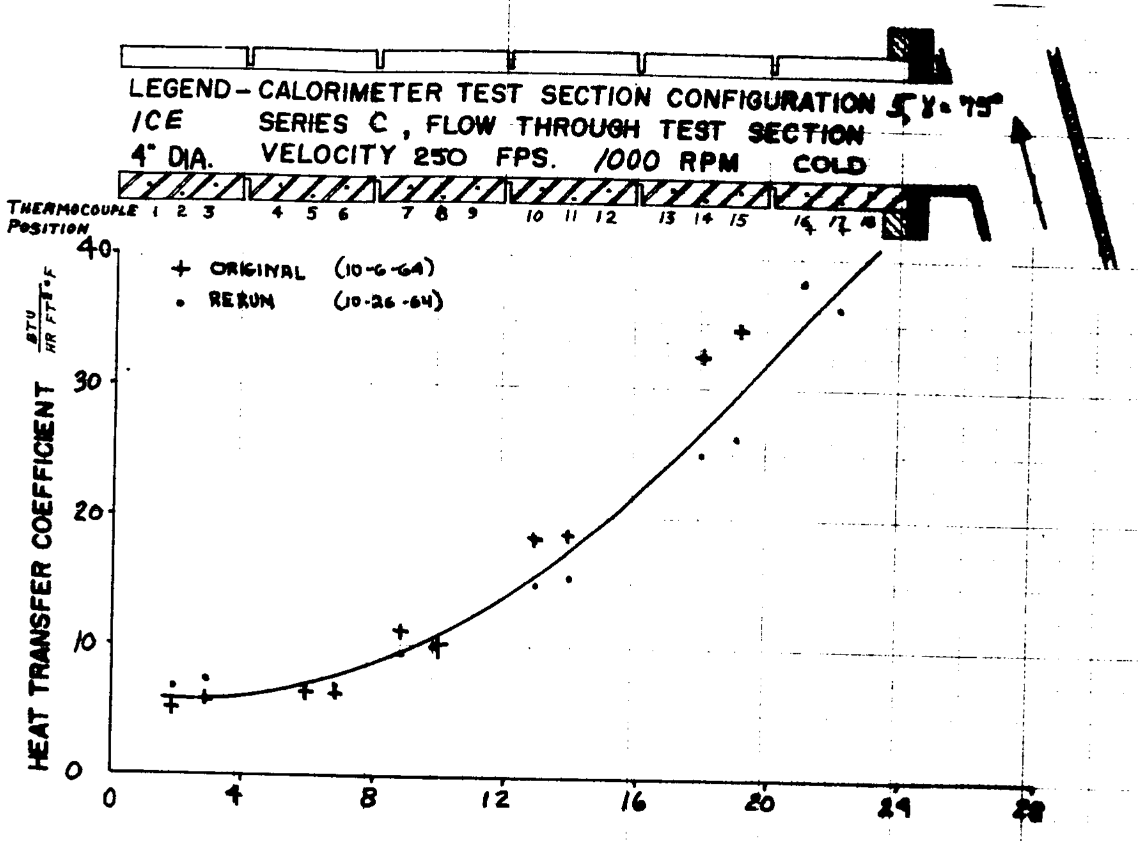


FIGURE A-79

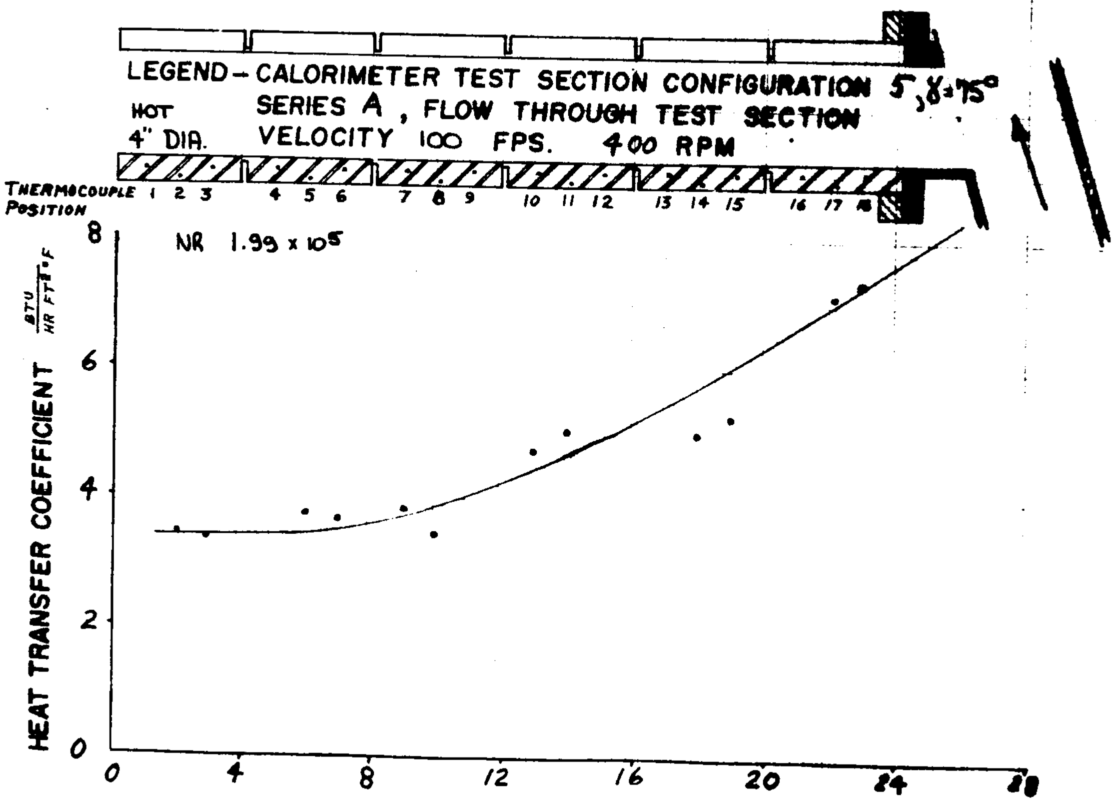


FIGURE A-80

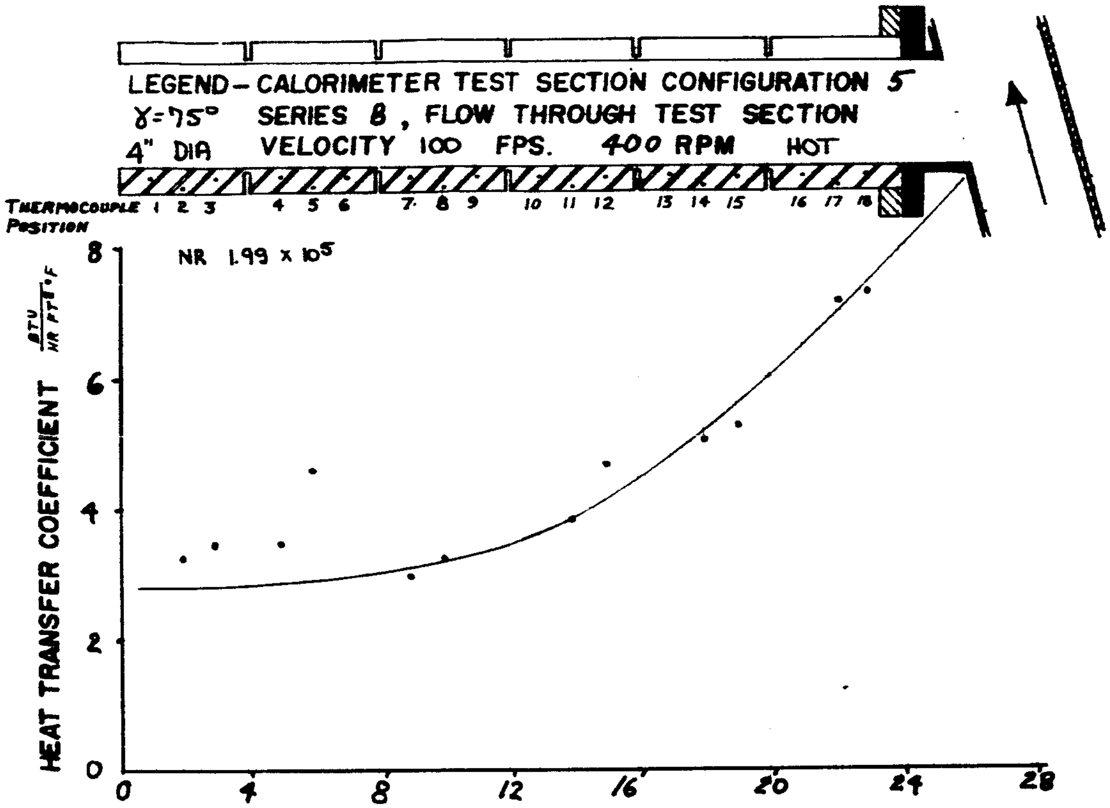


FIGURE A-81

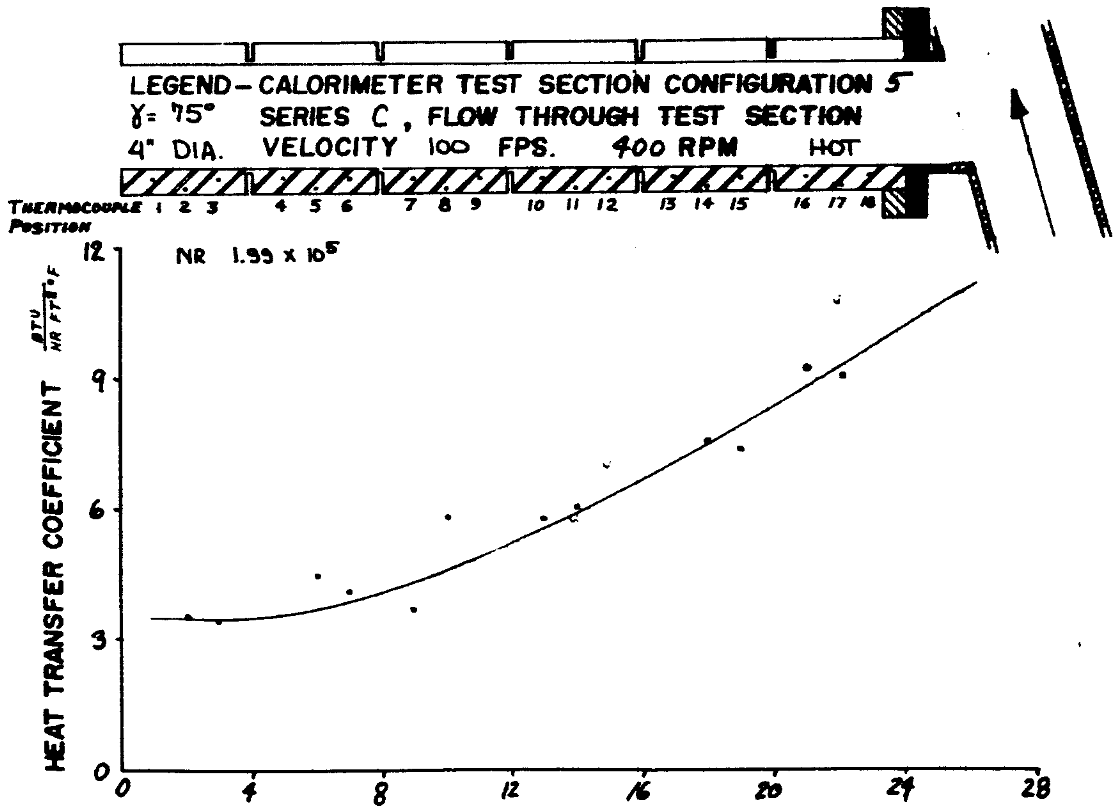


FIGURE A-82

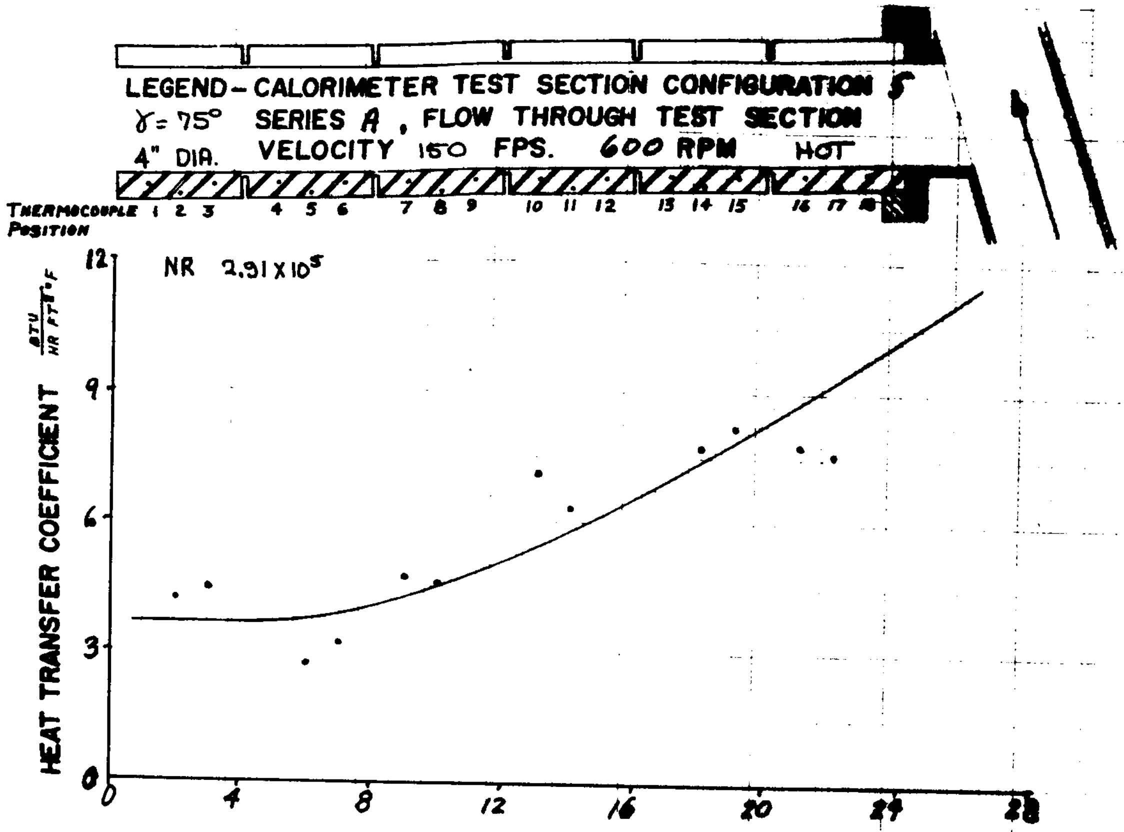


FIGURE A-83

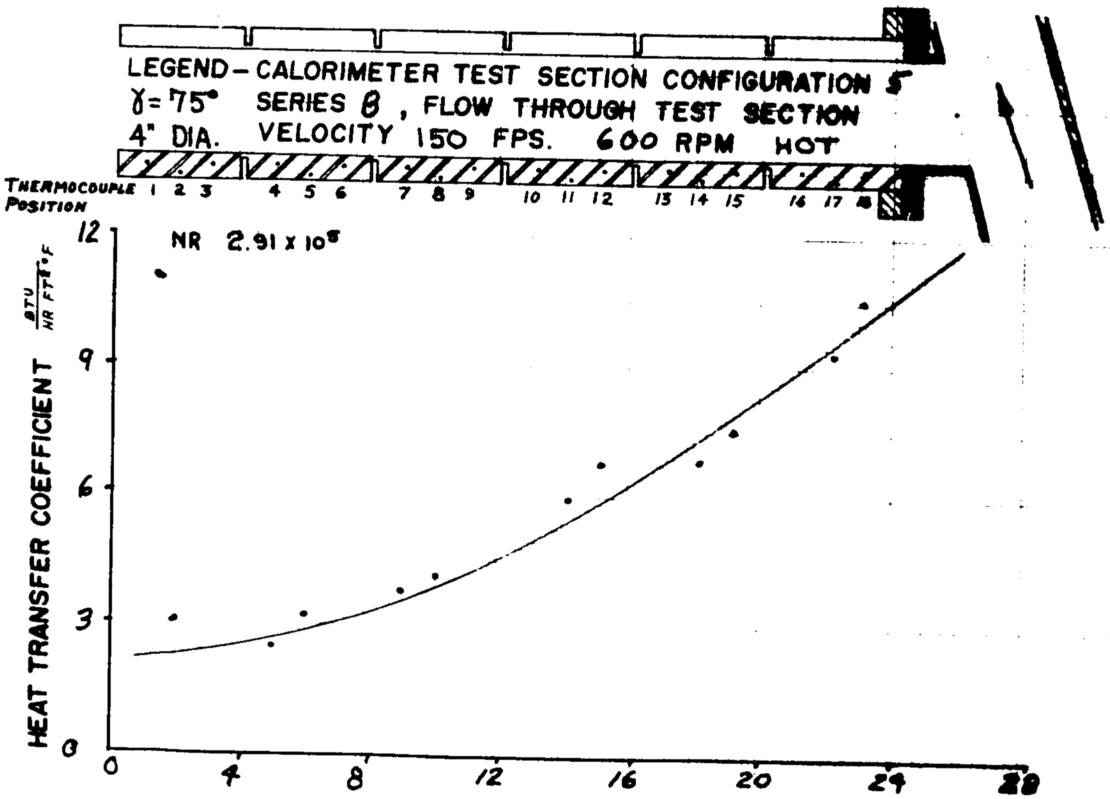


FIGURE A-84

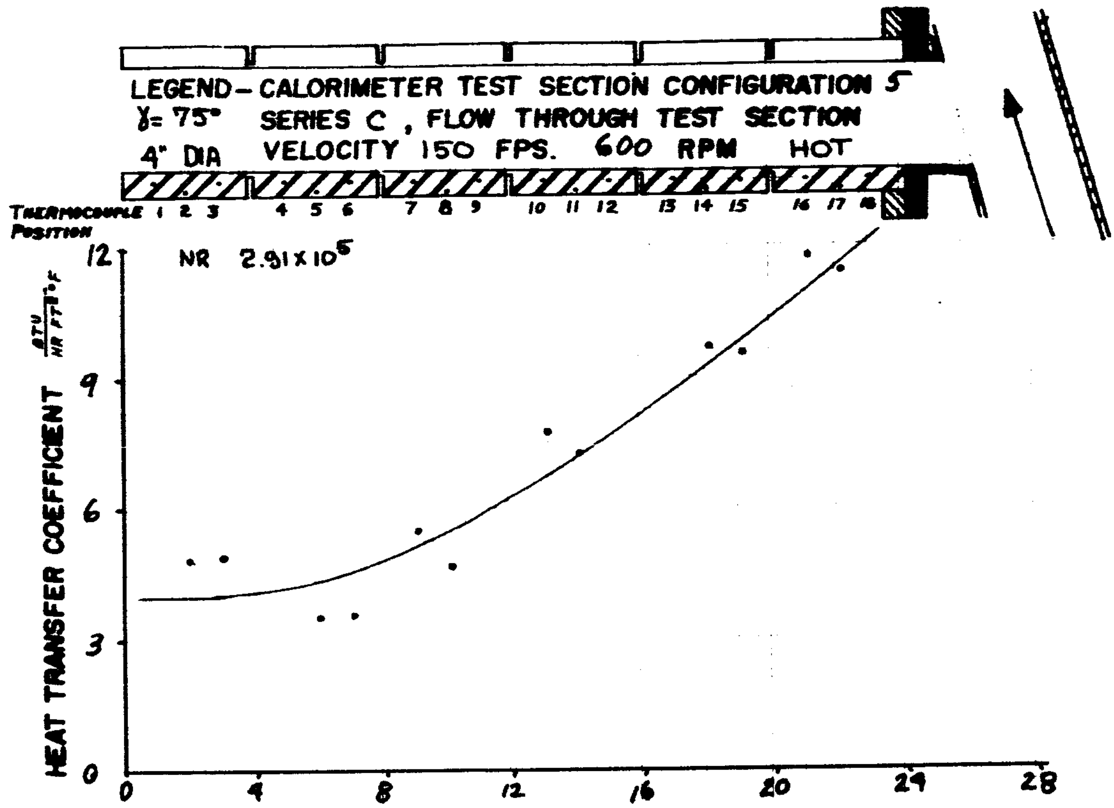


FIGURE A-85

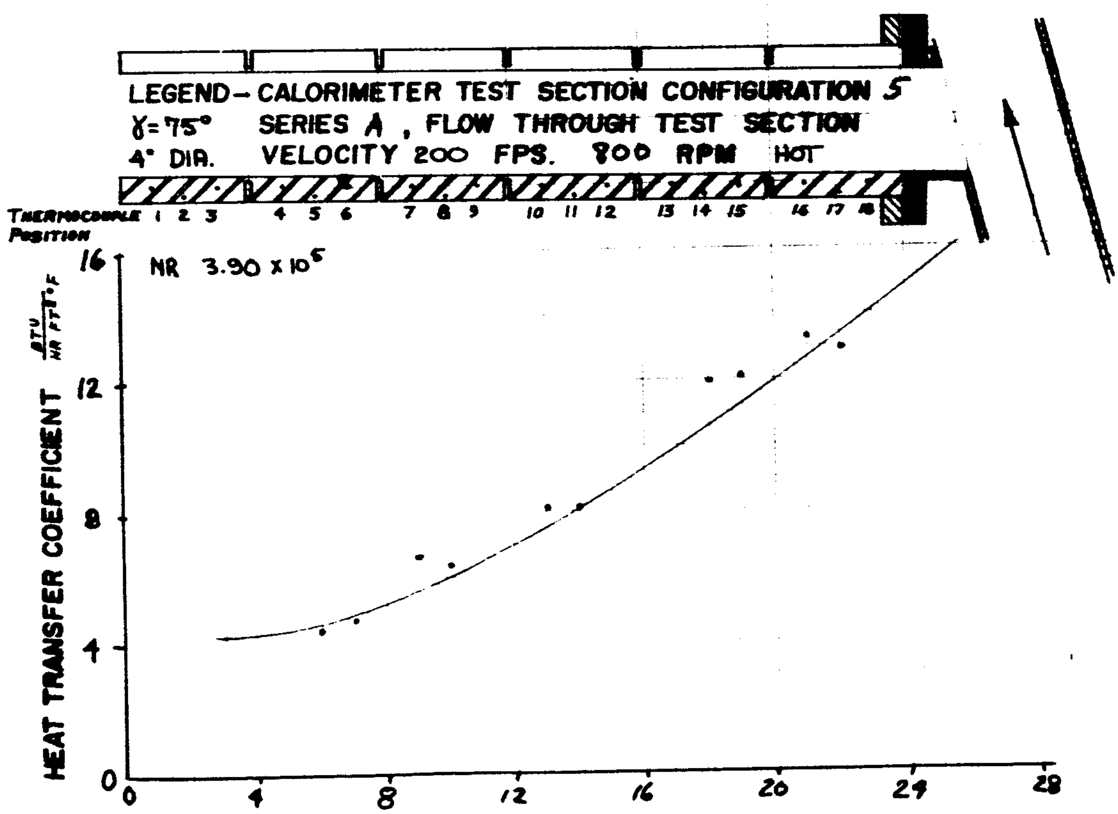


FIGURE A-86

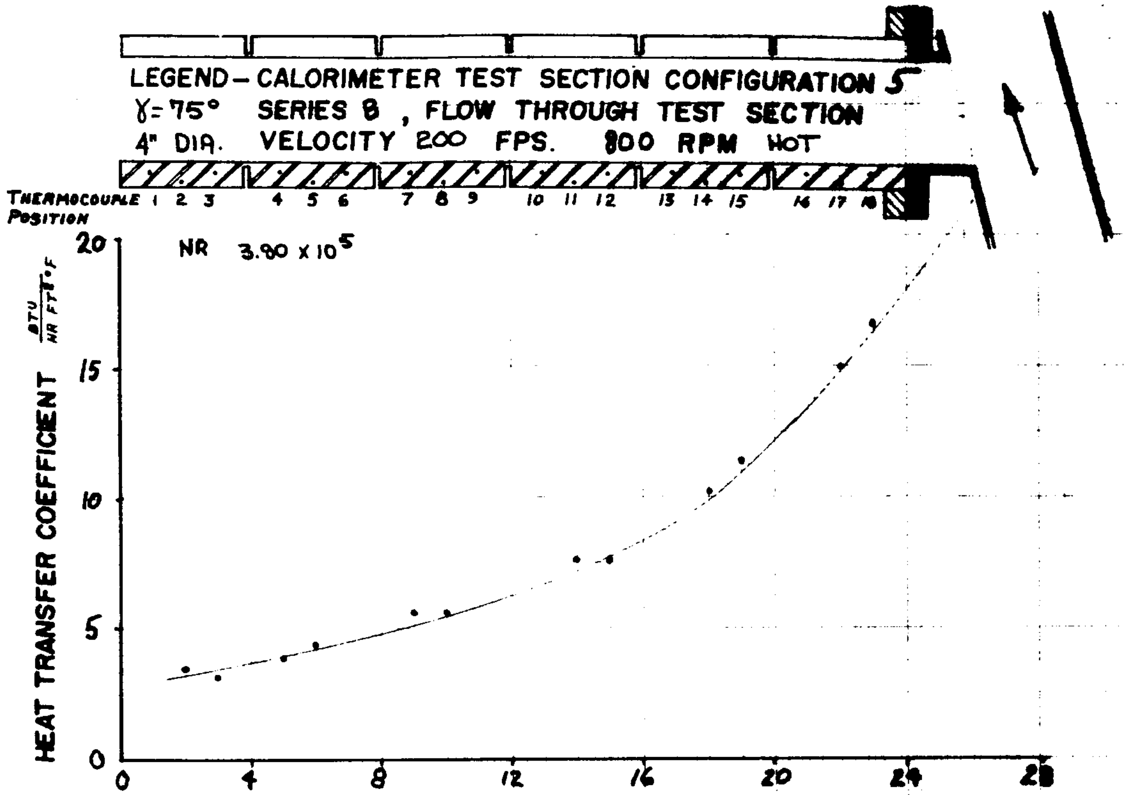


FIGURE A-87

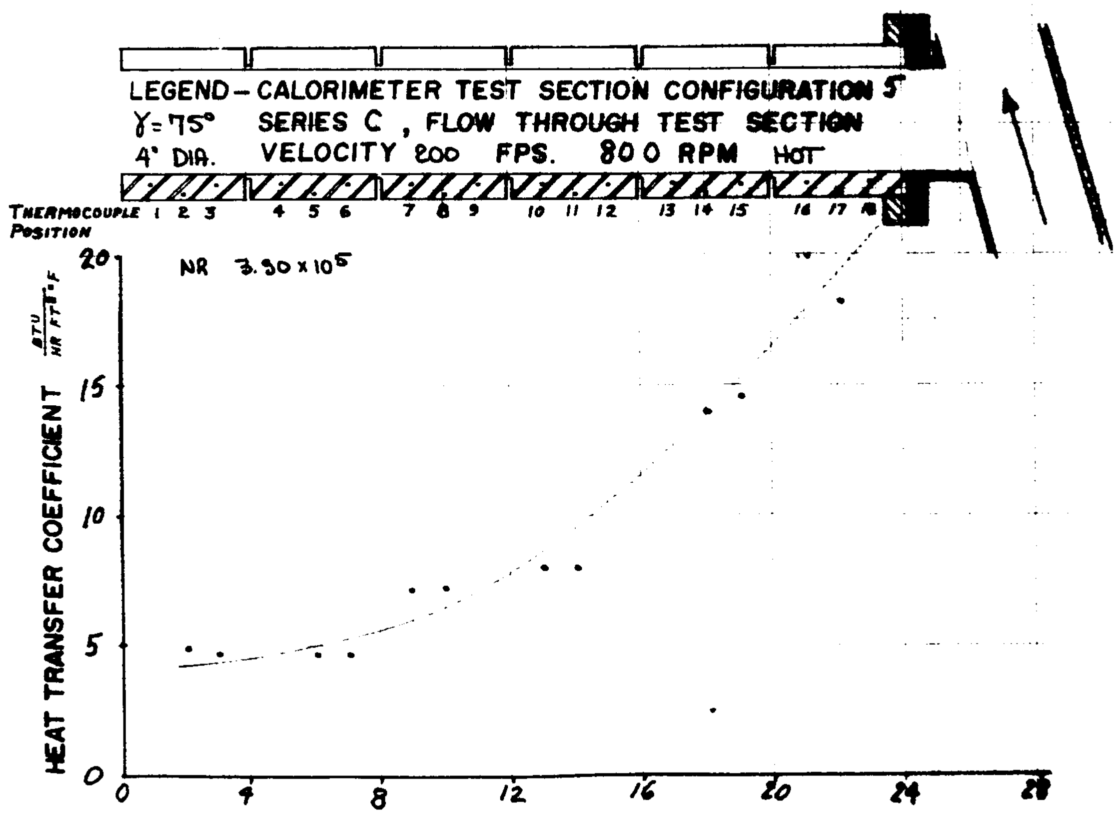


FIGURE A-88

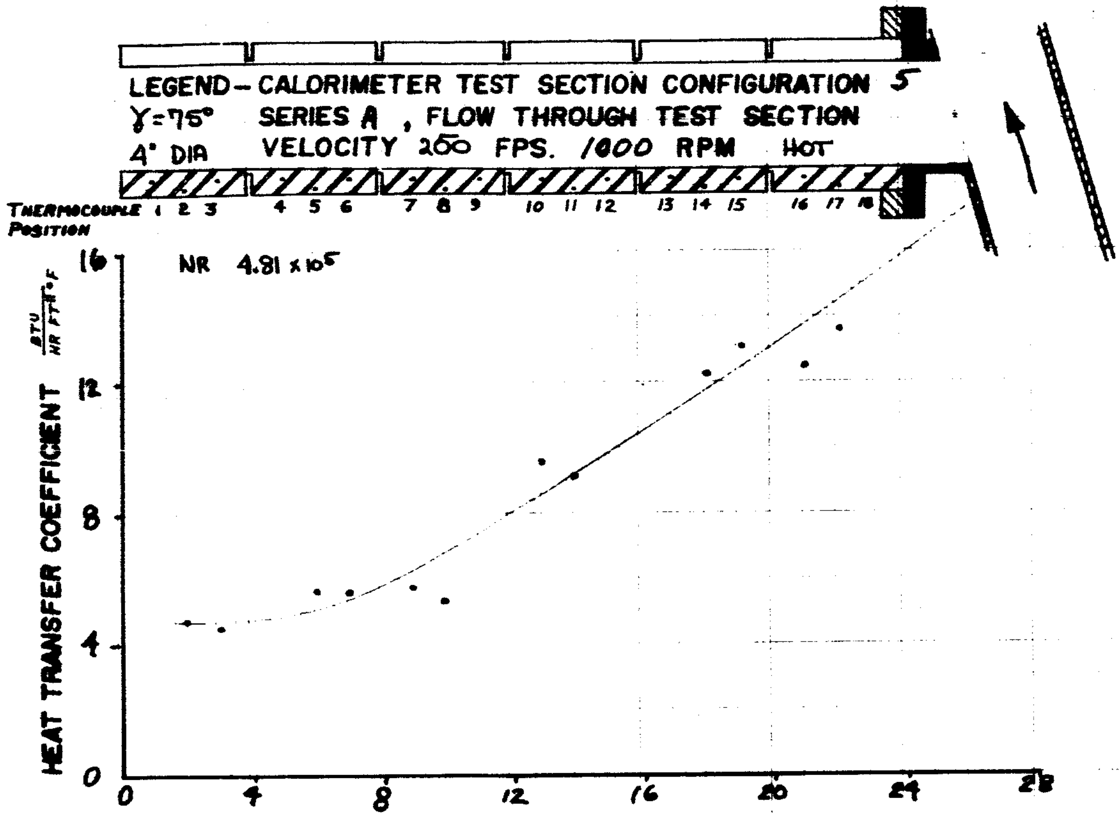


FIGURE A-89

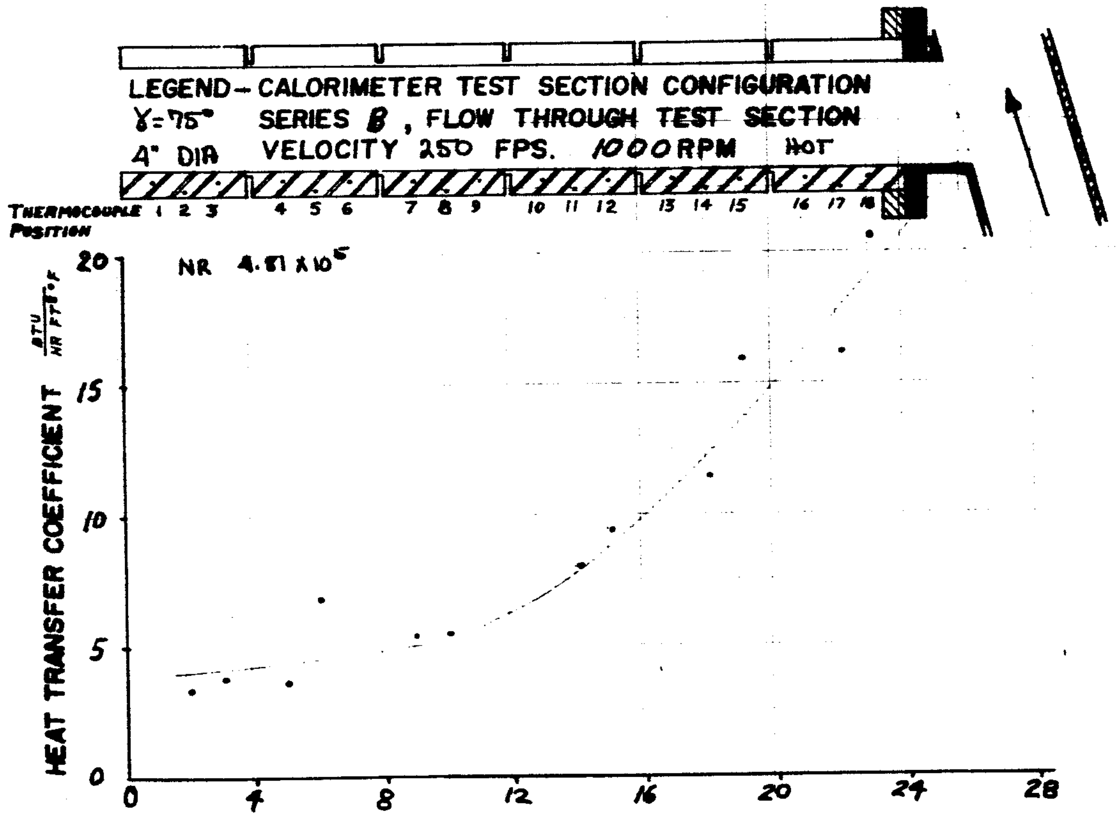


FIGURE A-90

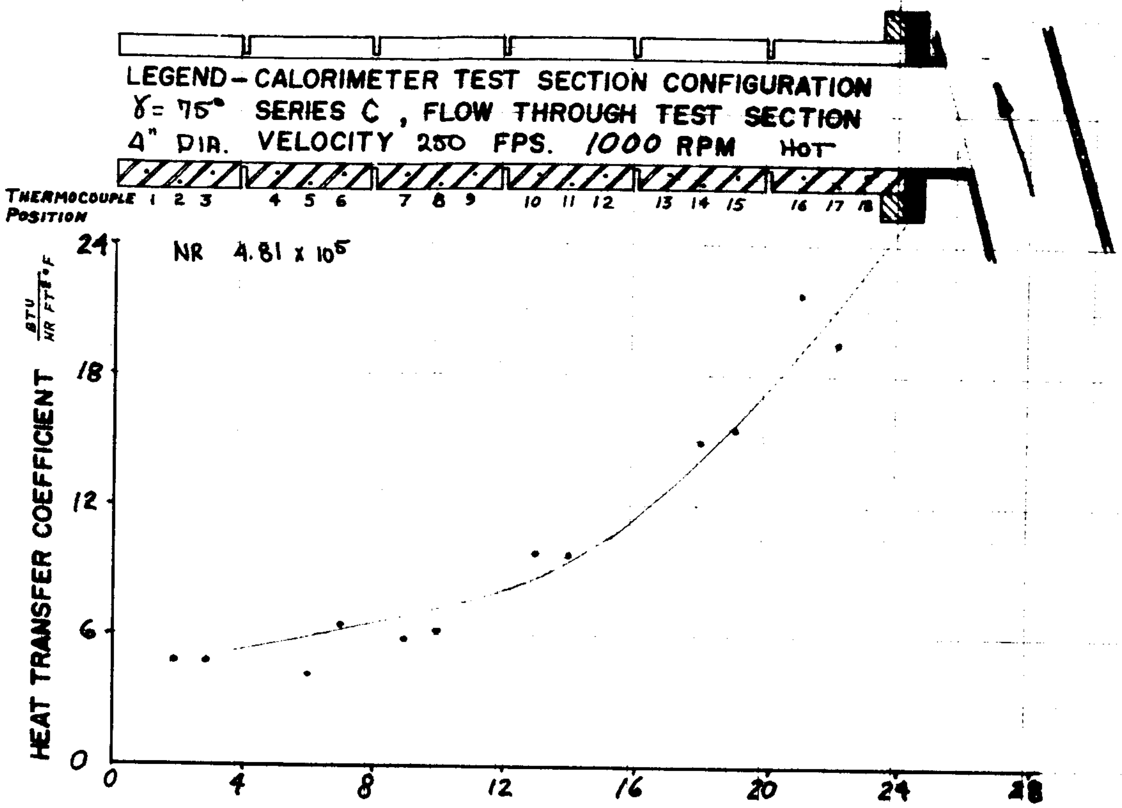


FIGURE A-91

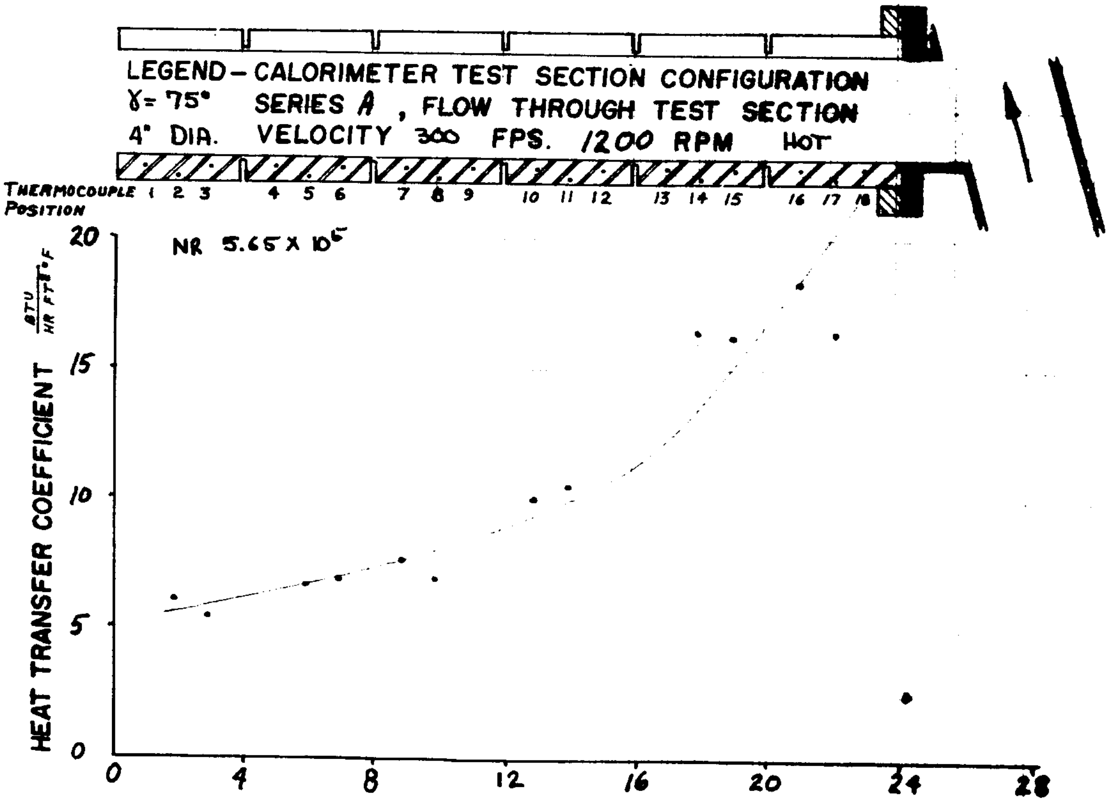


FIGURE A-92

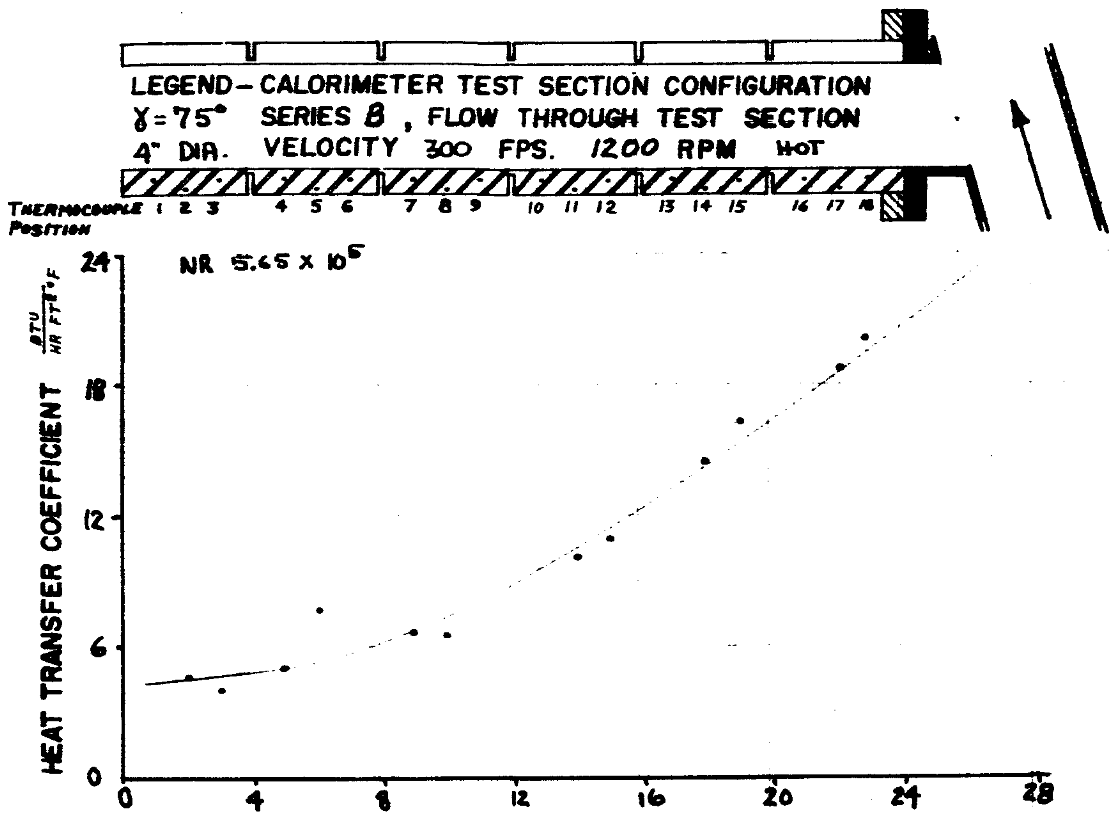


FIGURE A-93

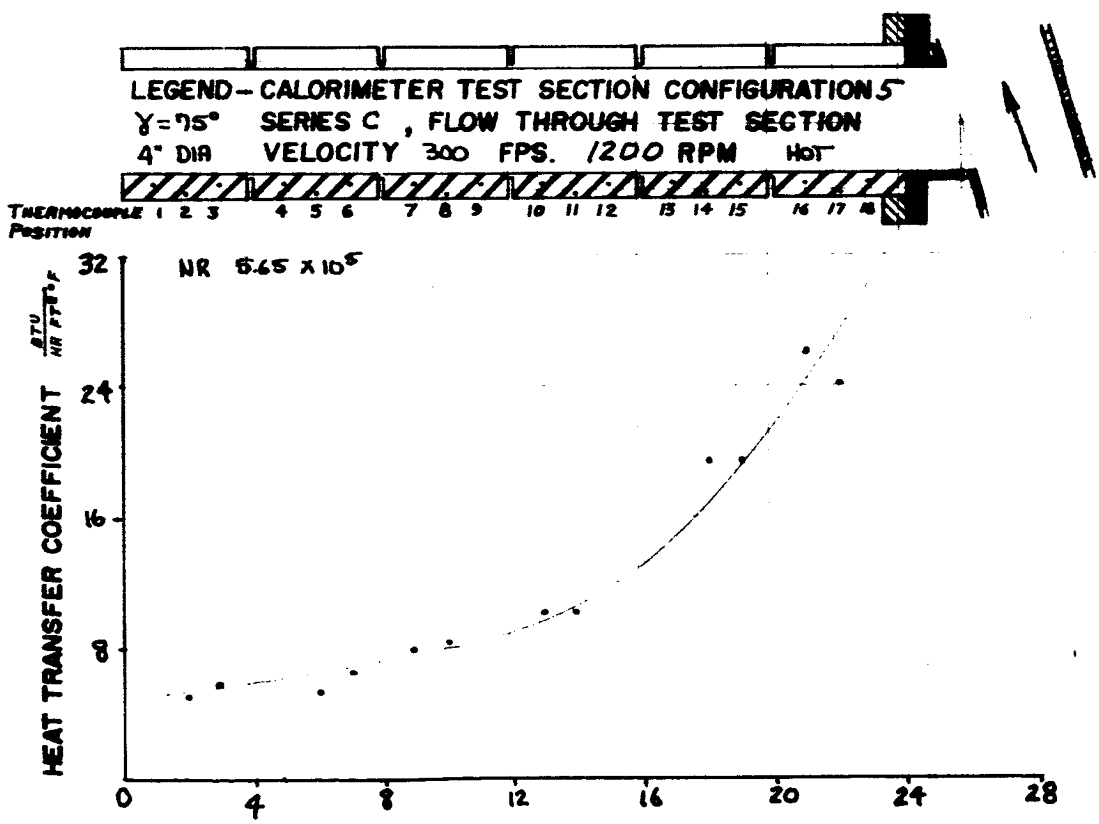


FIGURE A-94

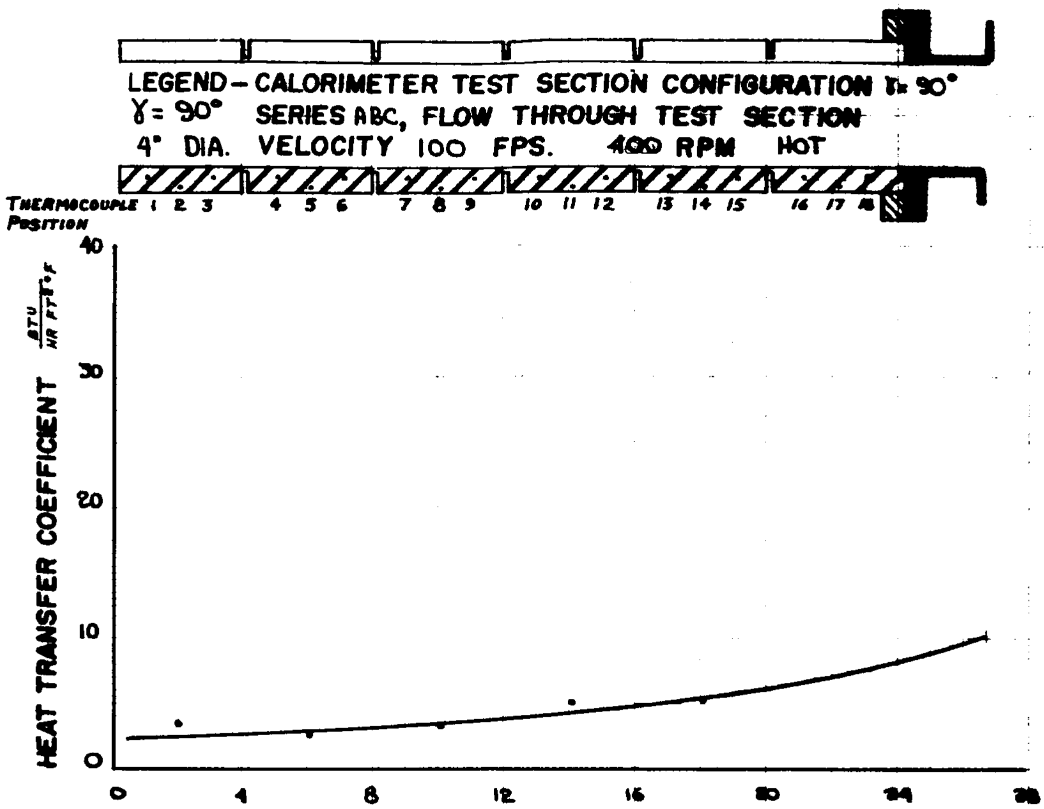


FIGURE A-95

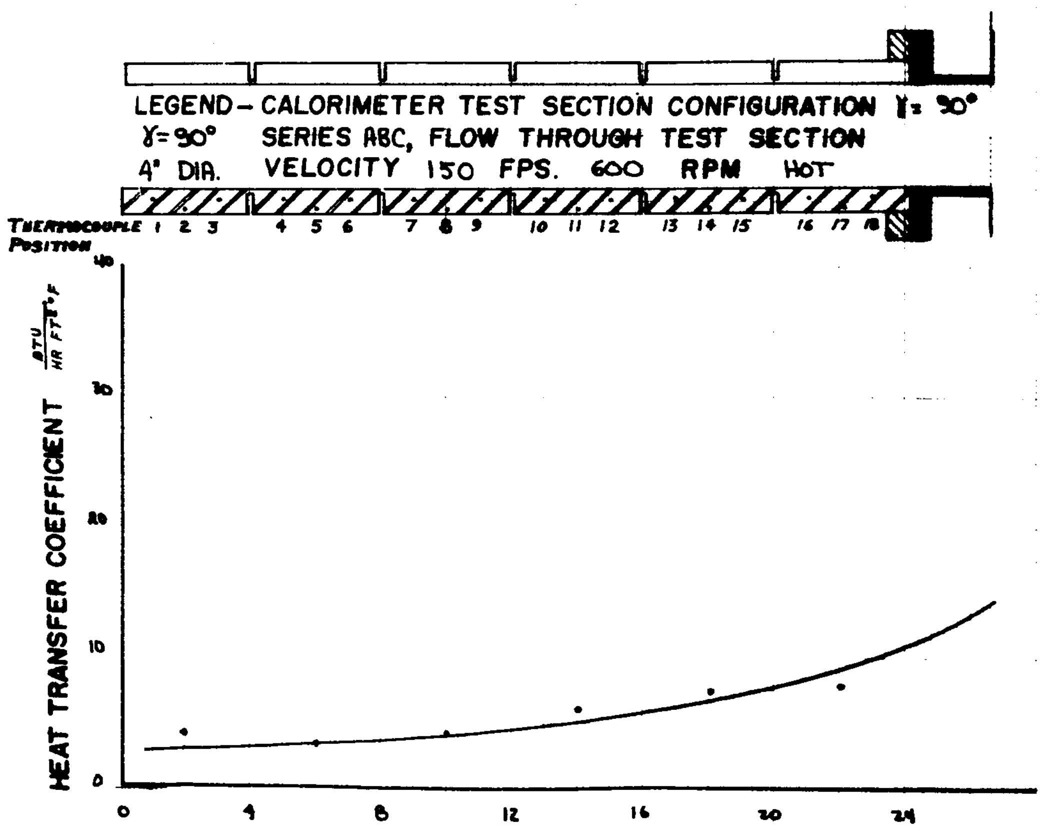


FIGURE A-96

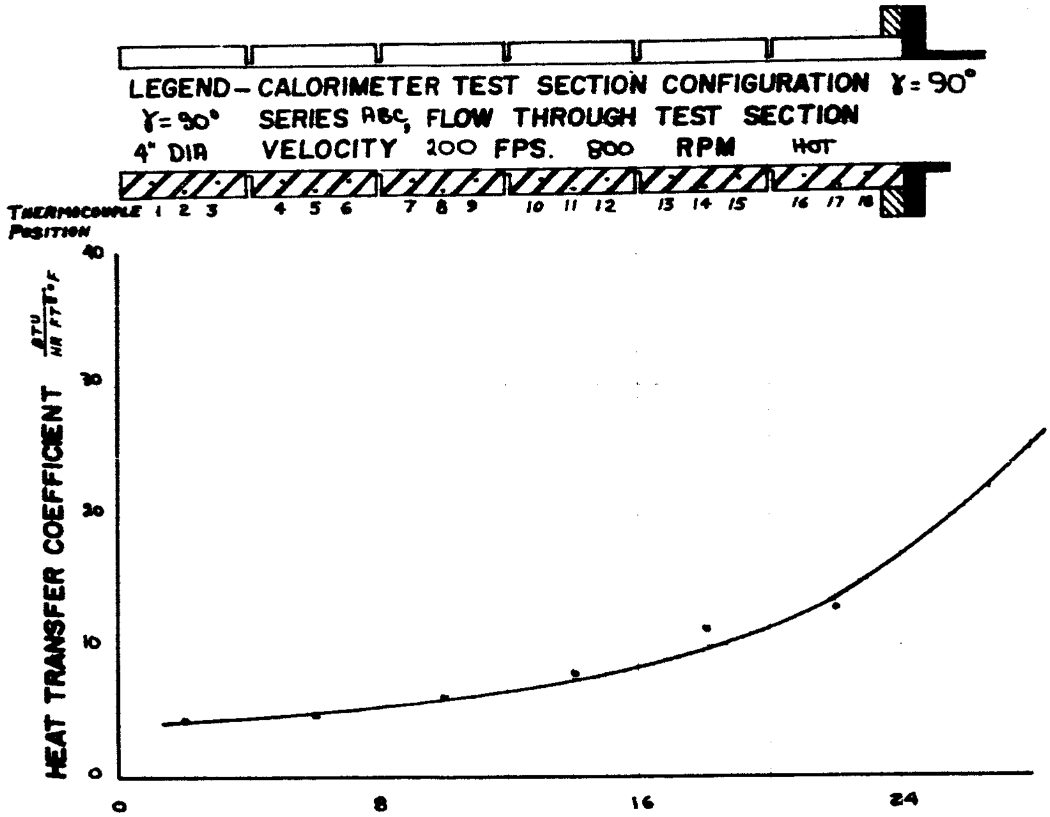


FIGURE A-97

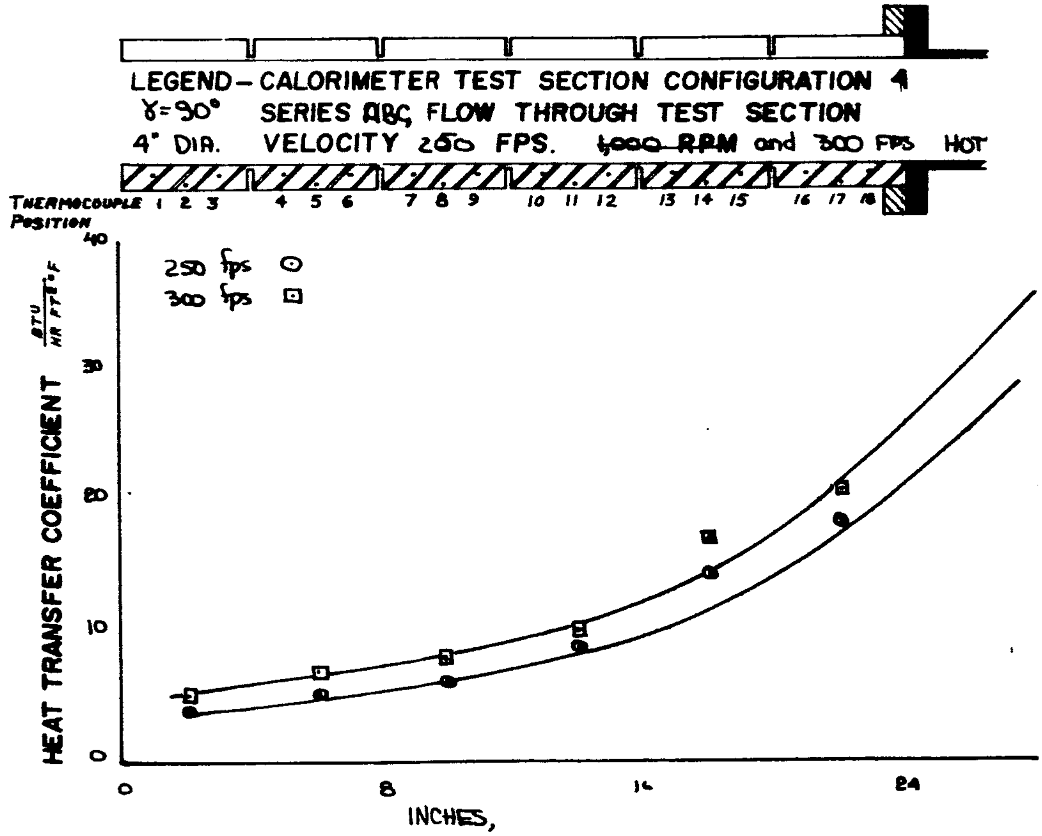


FIGURE A-98

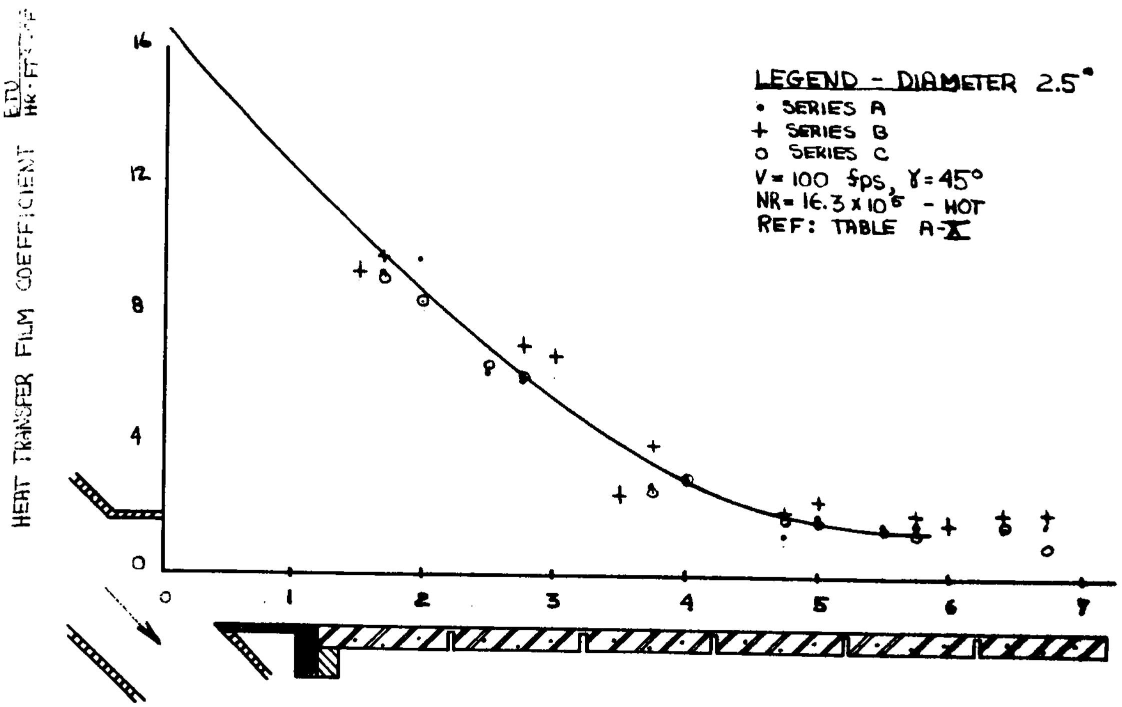


FIGURE A-99, HEAT TRANSFER FILM COEFFICIENT VERSUS CALORIMETER L/D

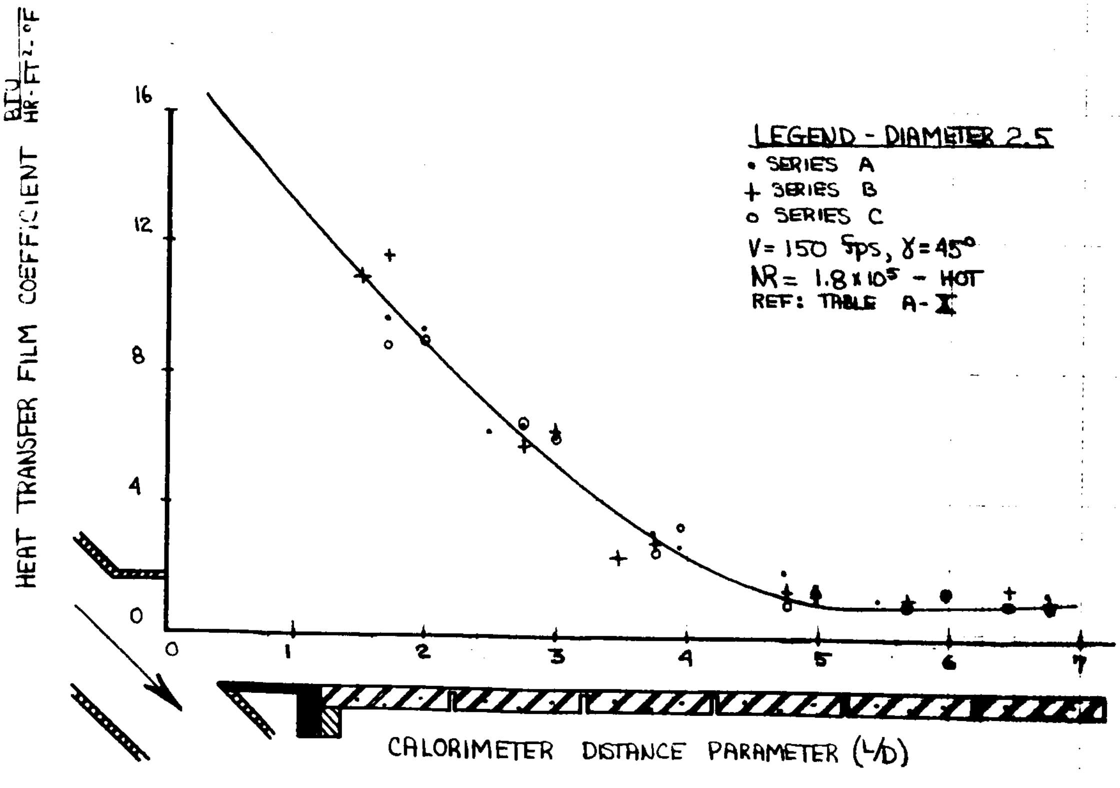


FIGURE A-100 HEAT TRANSFER FILM COEFFICIENT VERSUS CALORIMETER L/D

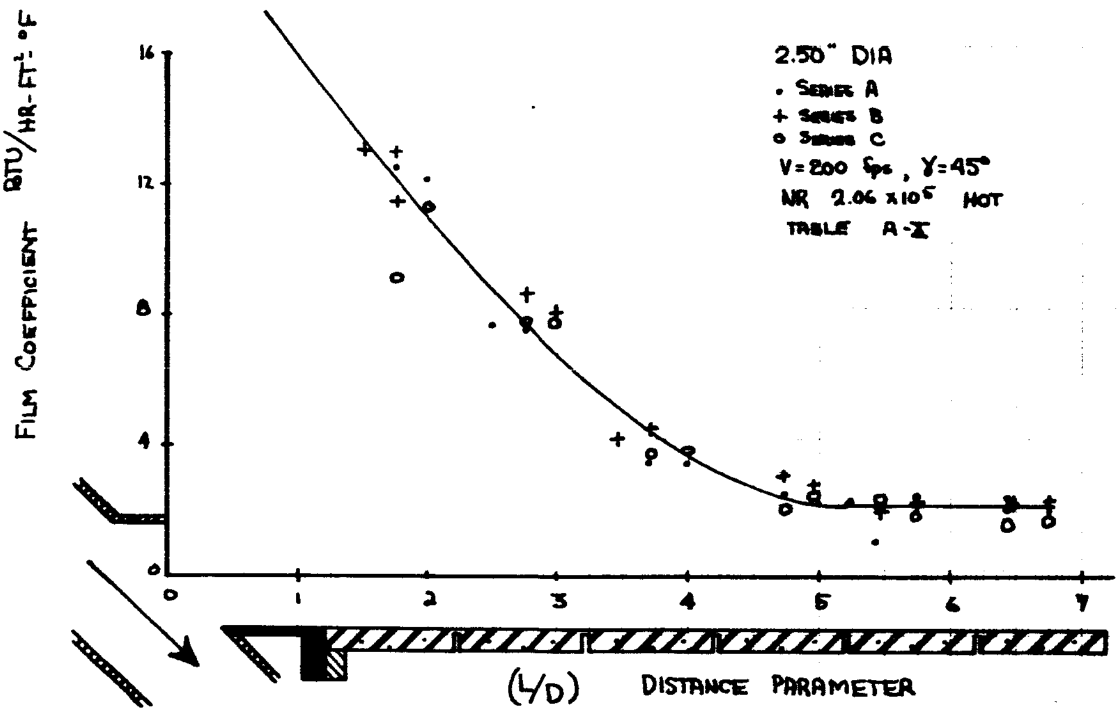


FIGURE A-101

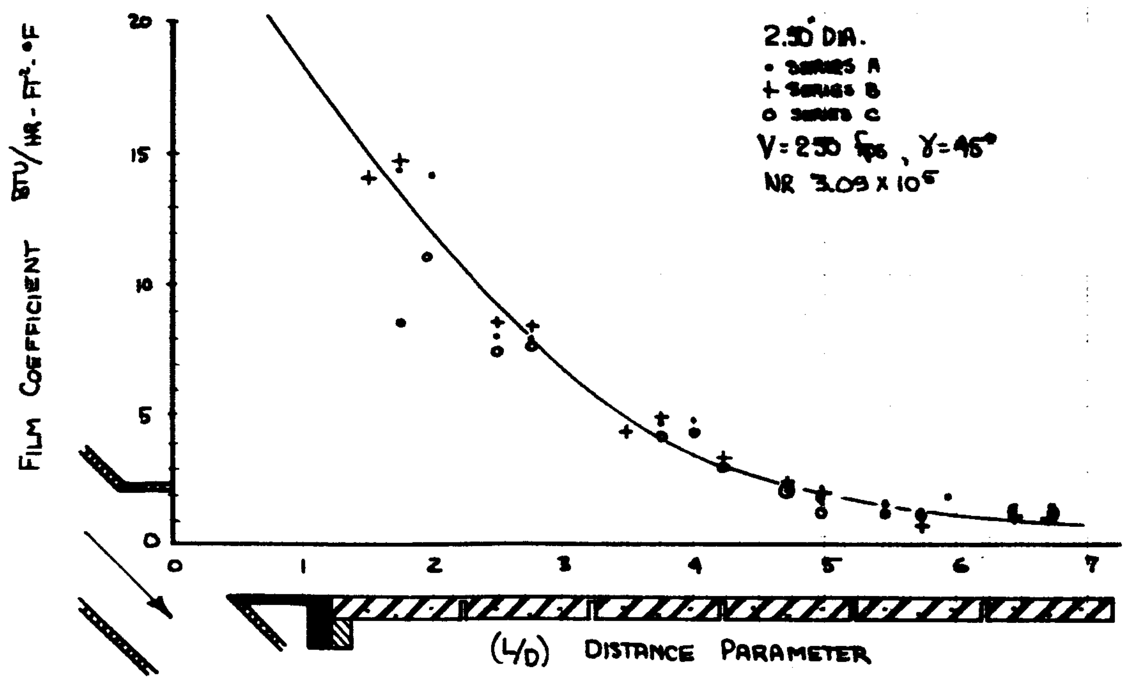


FIGURE A-102

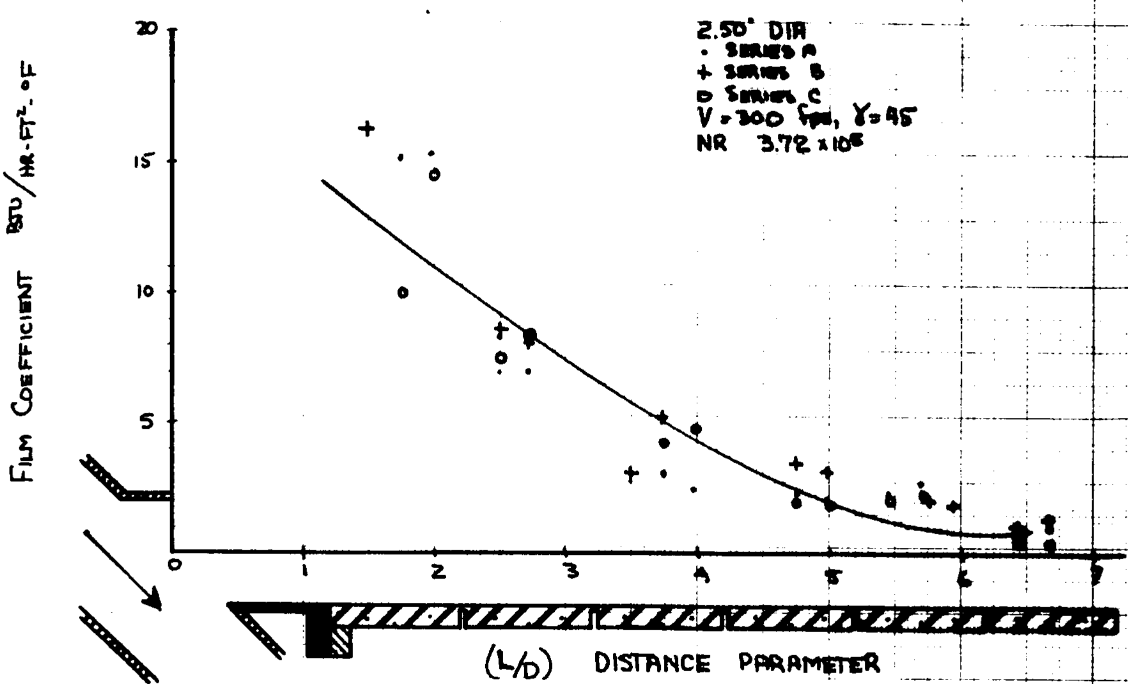


FIGURE A-103

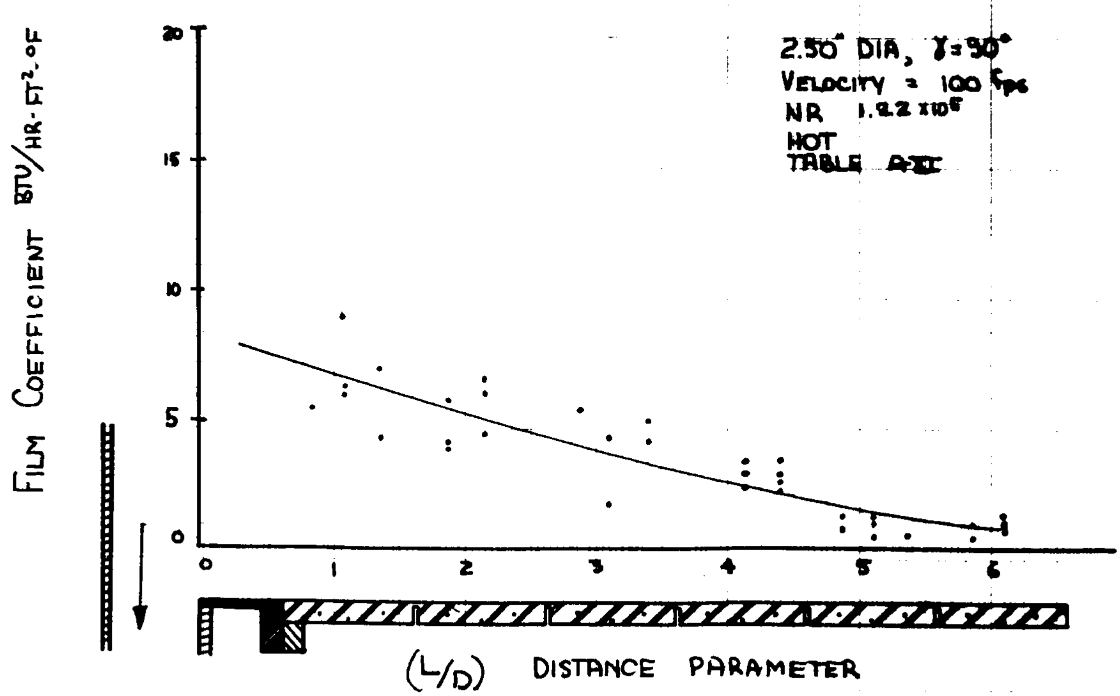


FIGURE A-104

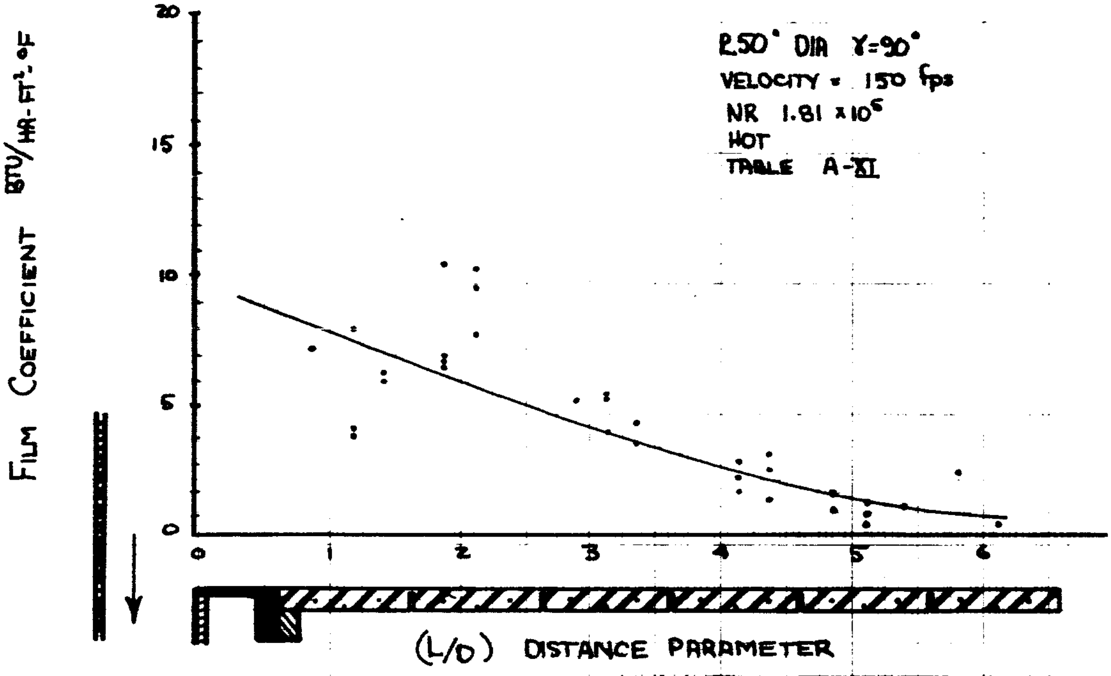


FIGURE A-105

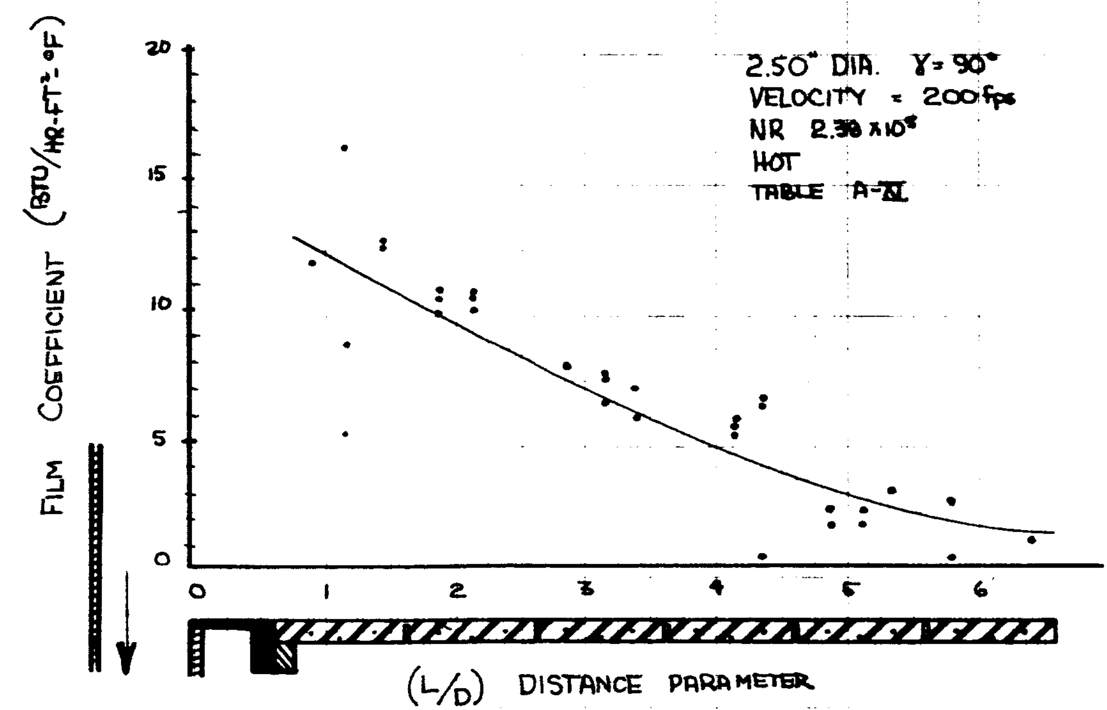


FIGURE A-106

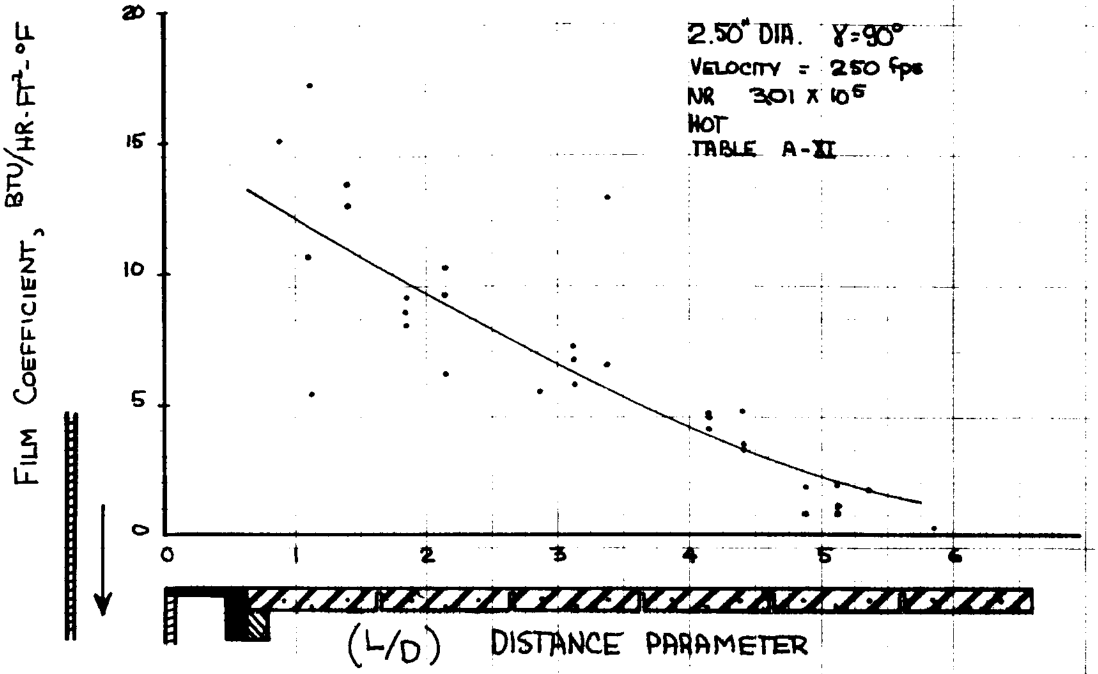


FIGURE A-107

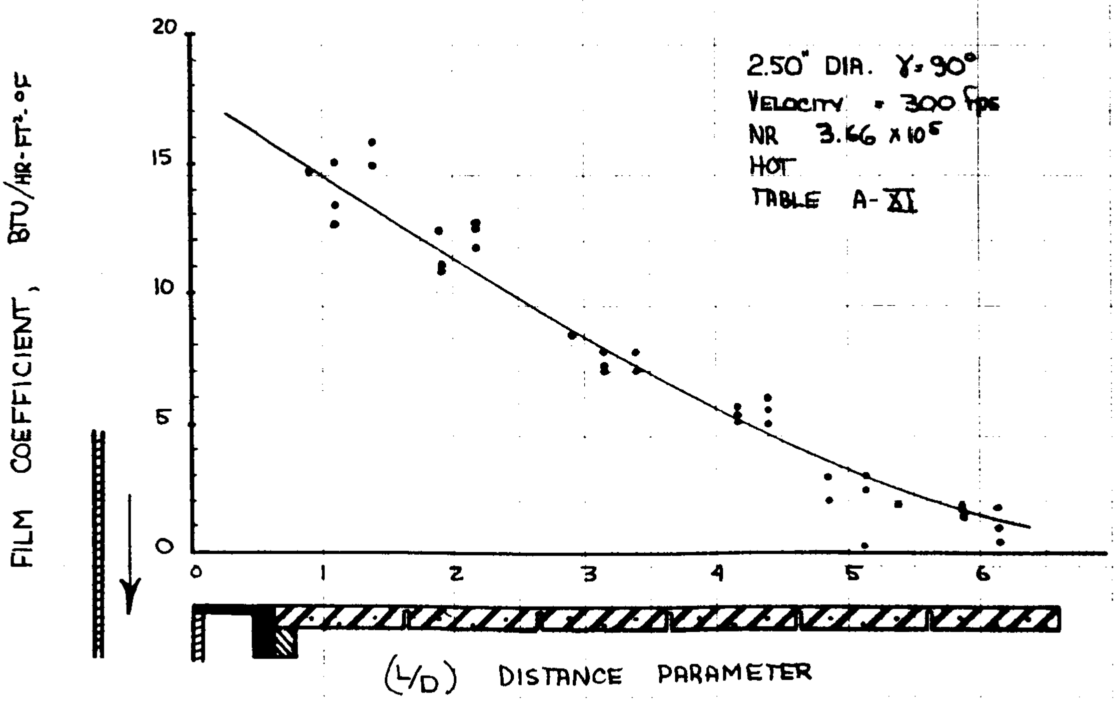


FIGURE A-108

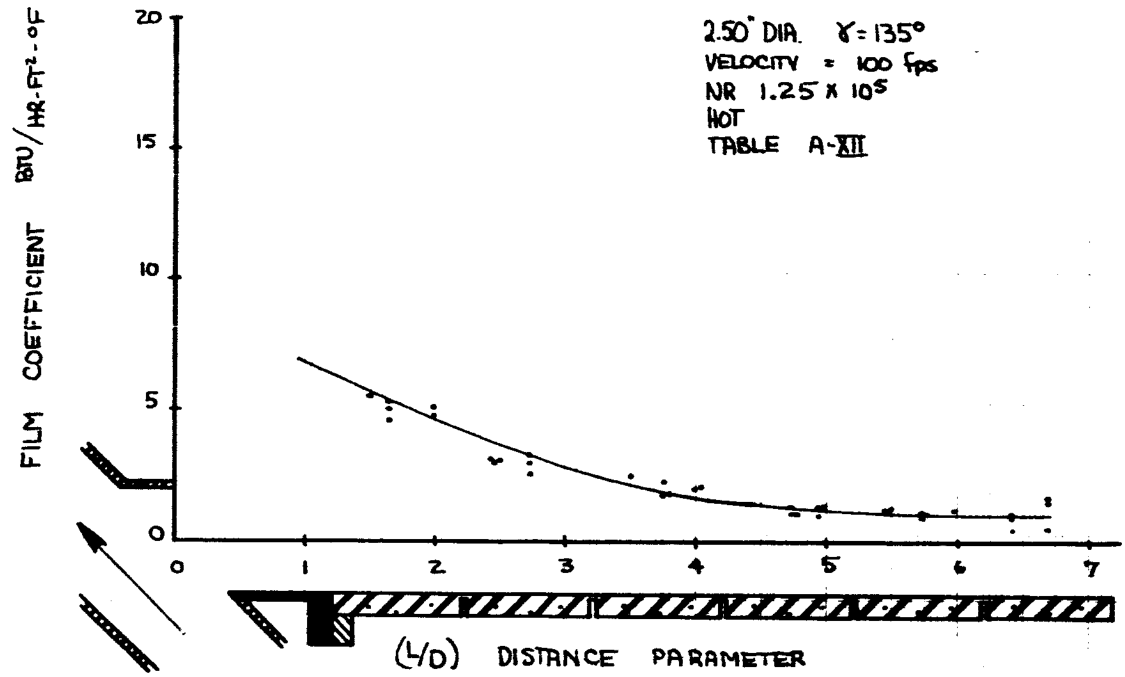


FIGURE A-109

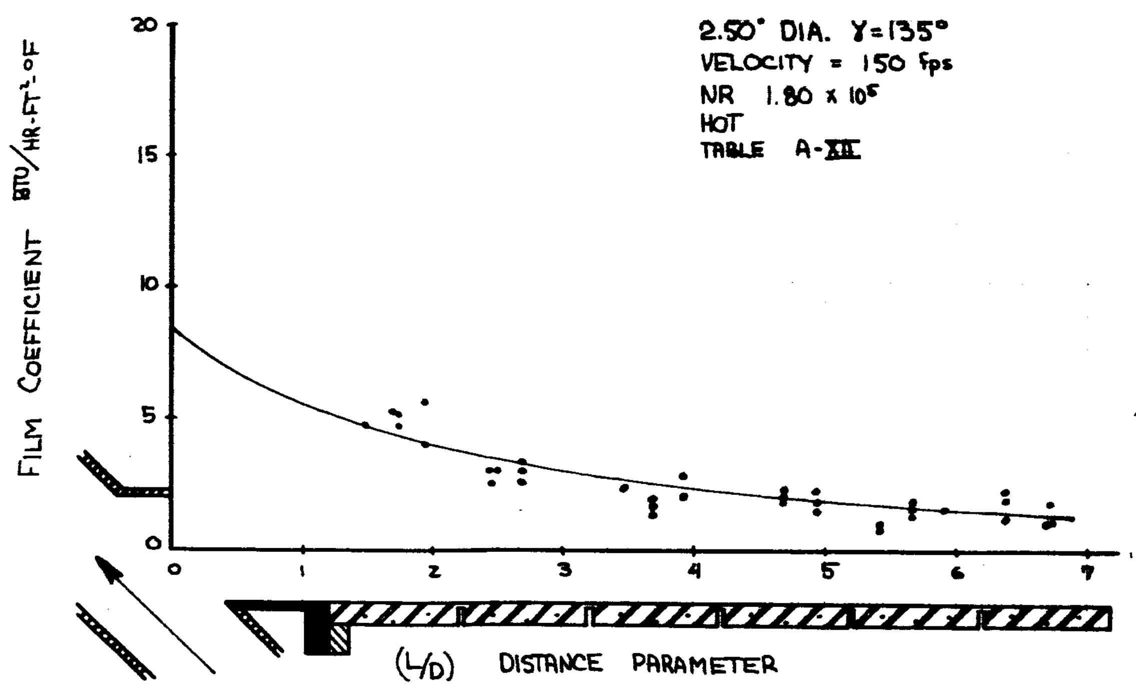


FIGURE A-110

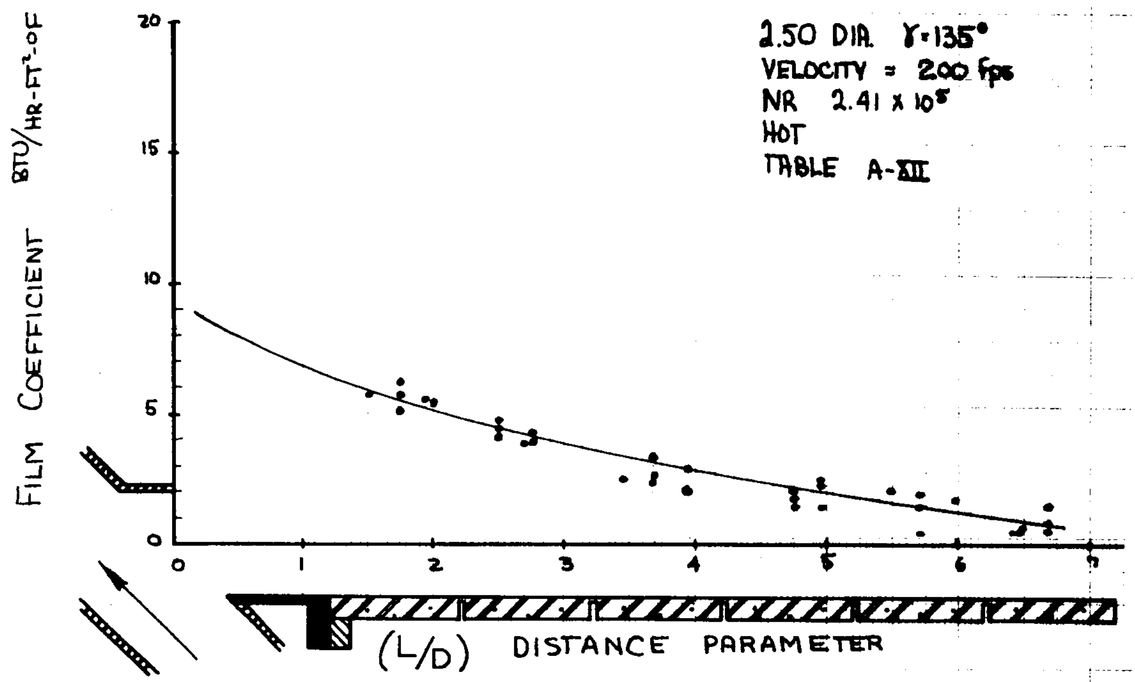


FIGURE A-110-A

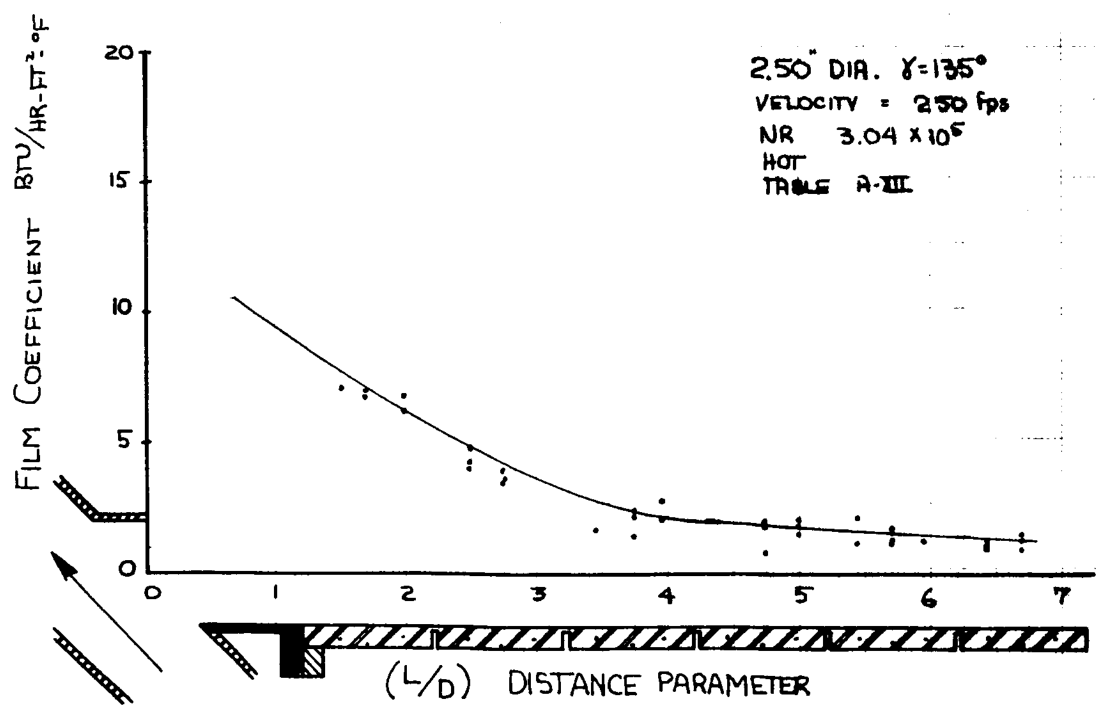


FIGURE A-111

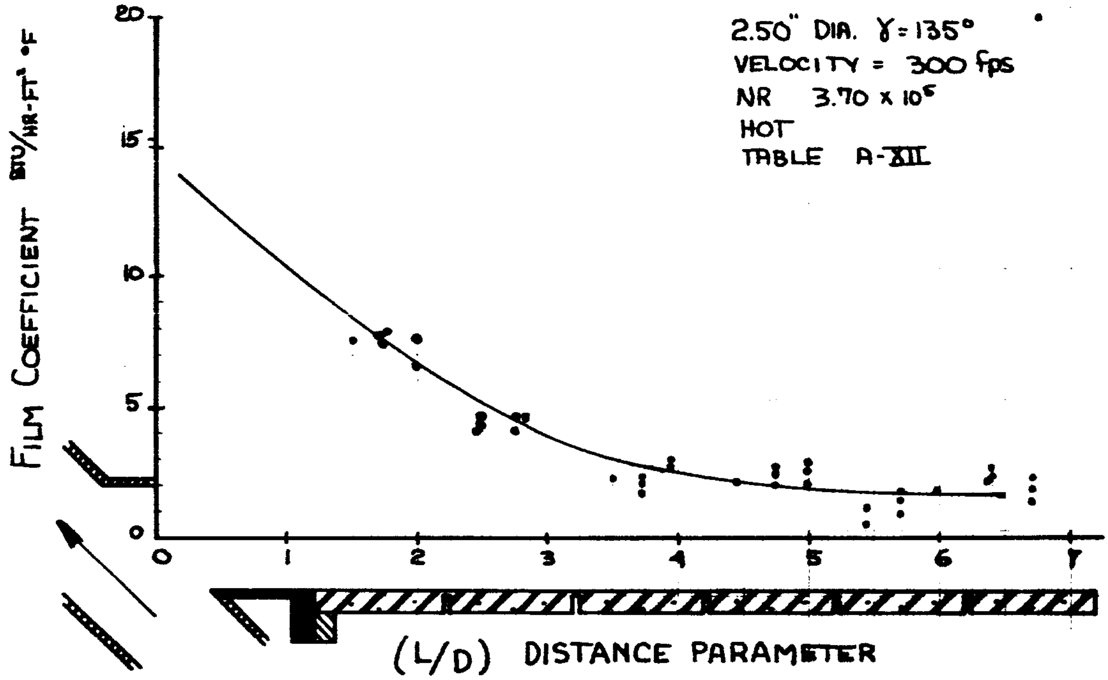


FIGURE A-112

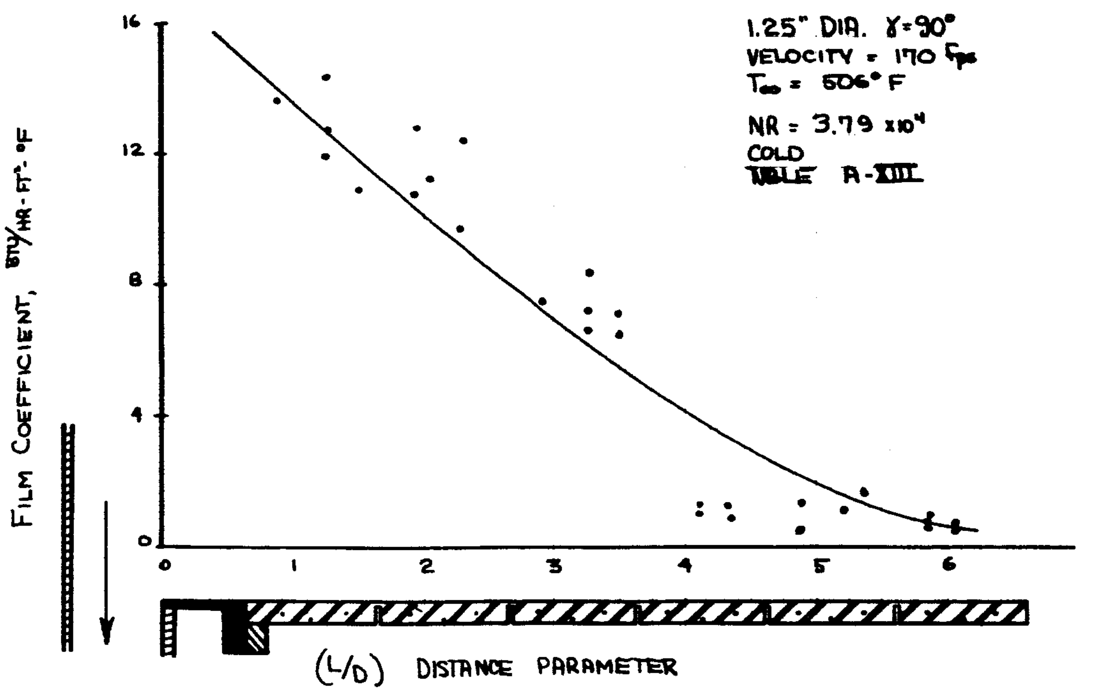


FIGURE A-113

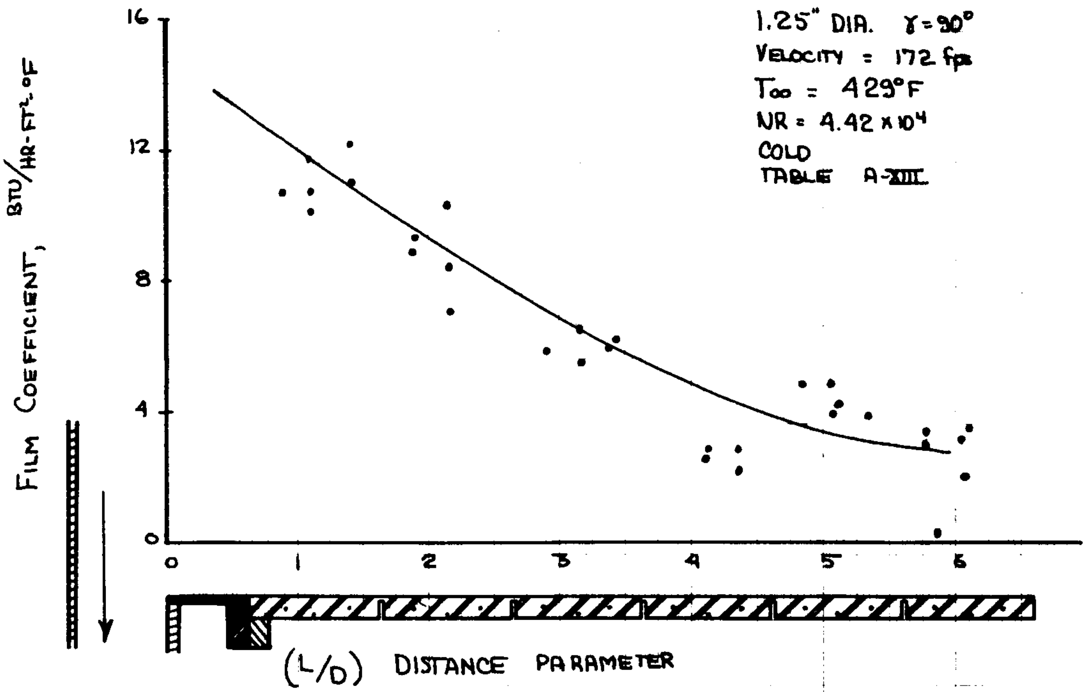


FIGURE A-114

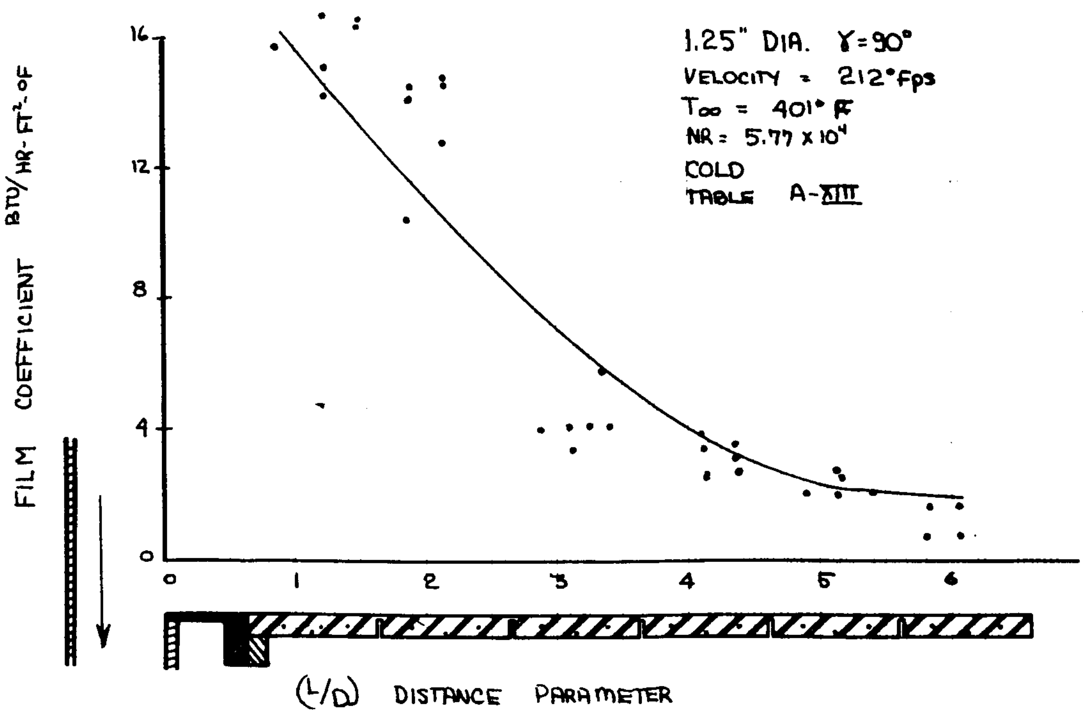


FIGURE A-115

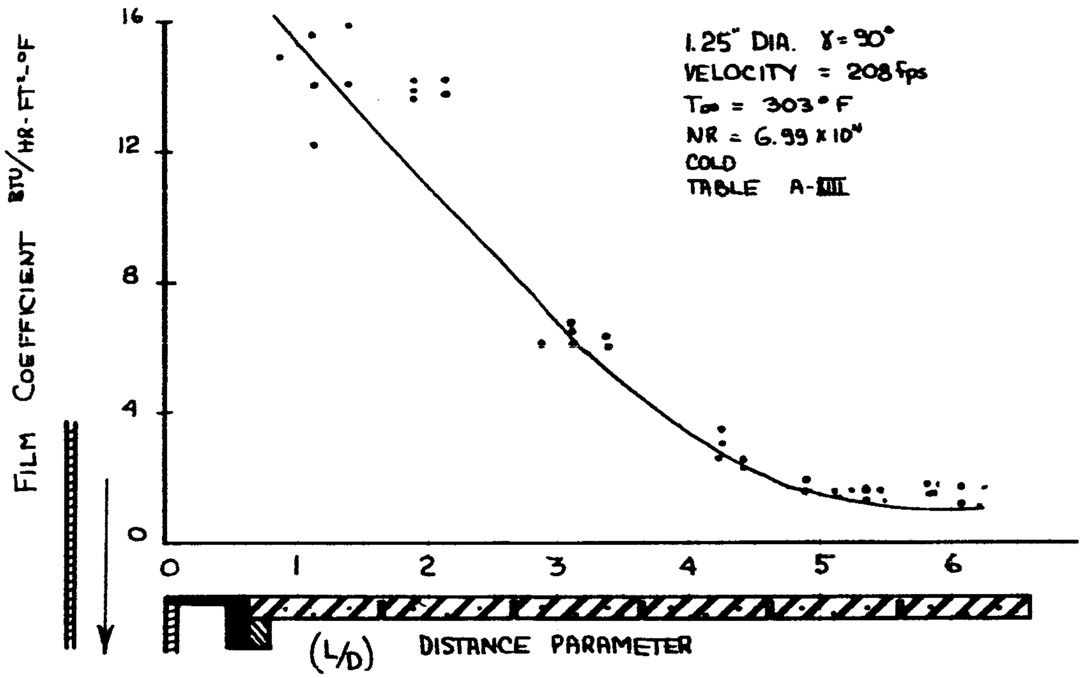


FIGURE A-116

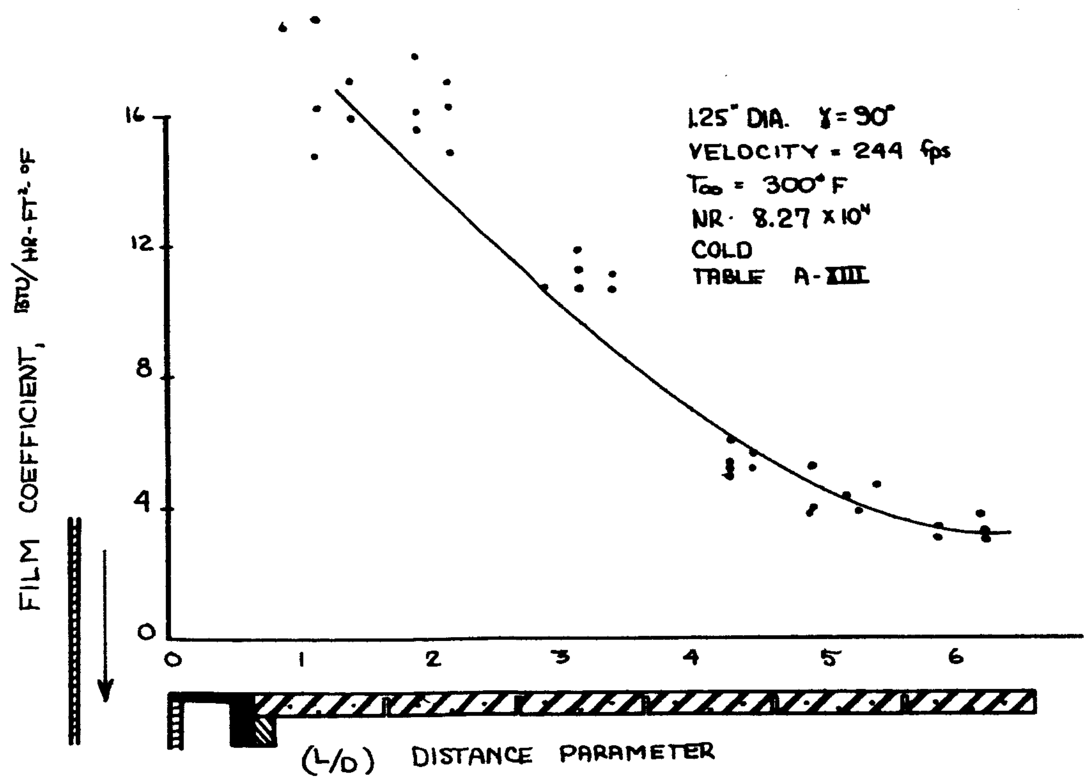


FIGURE A-117

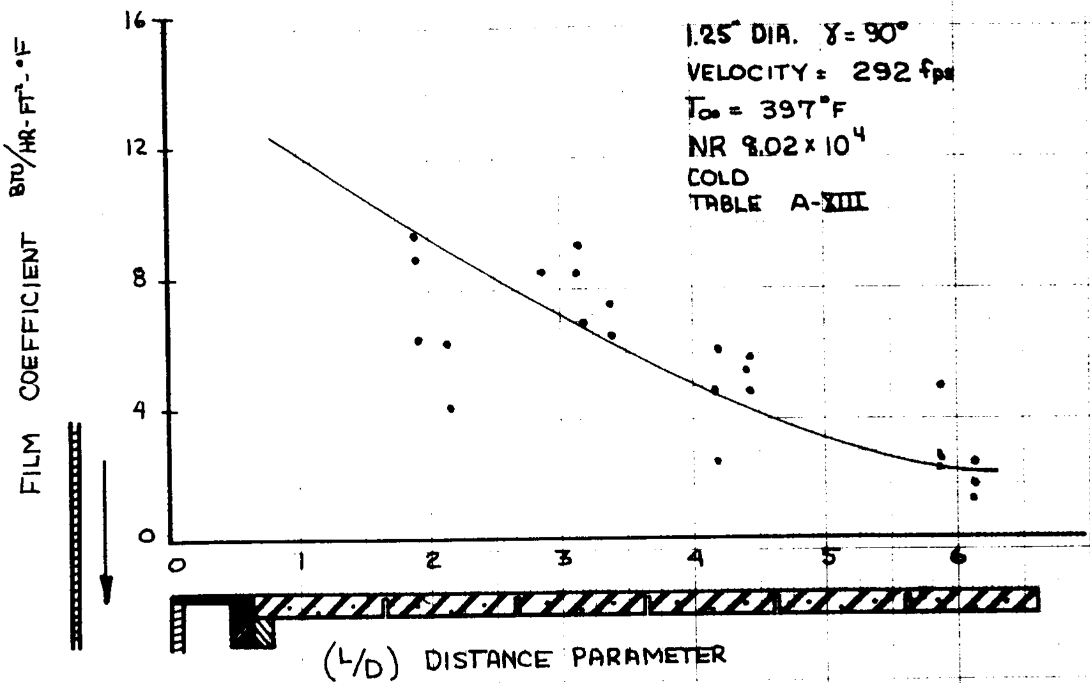


FIGURE A-118

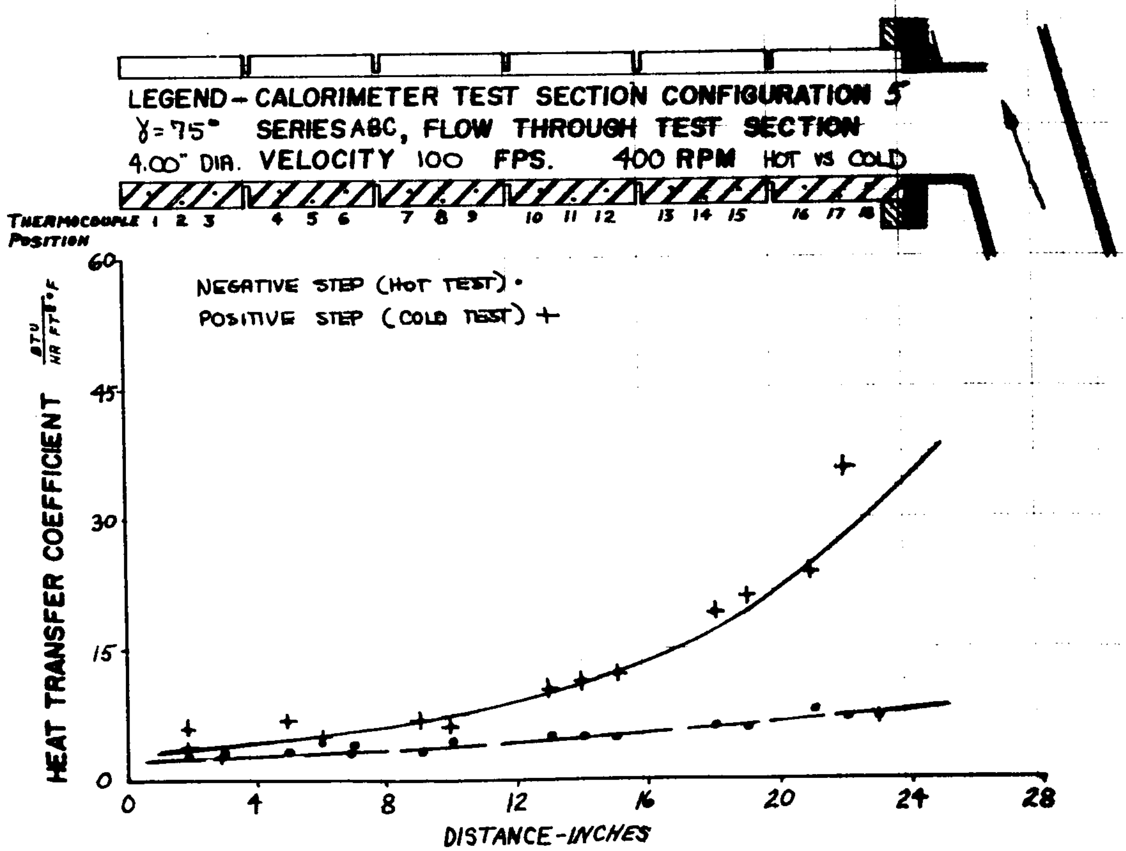


FIGURE A-119

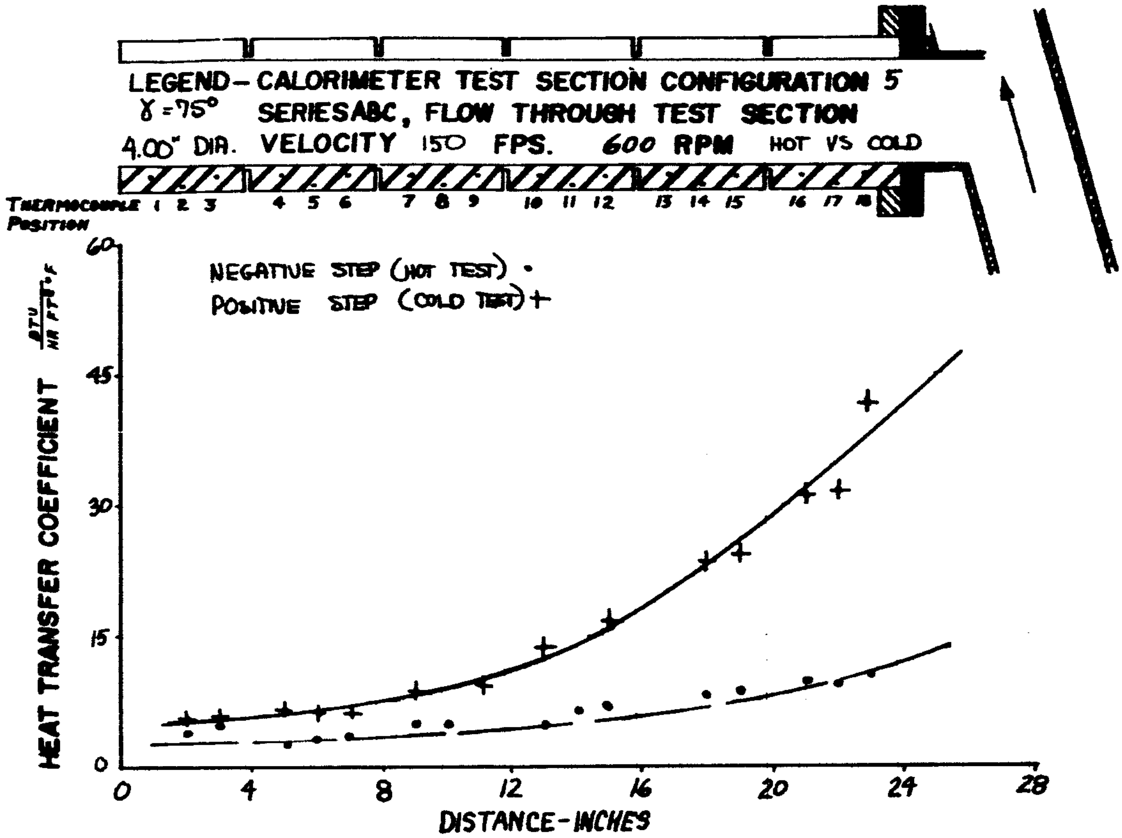


FIGURE A-120

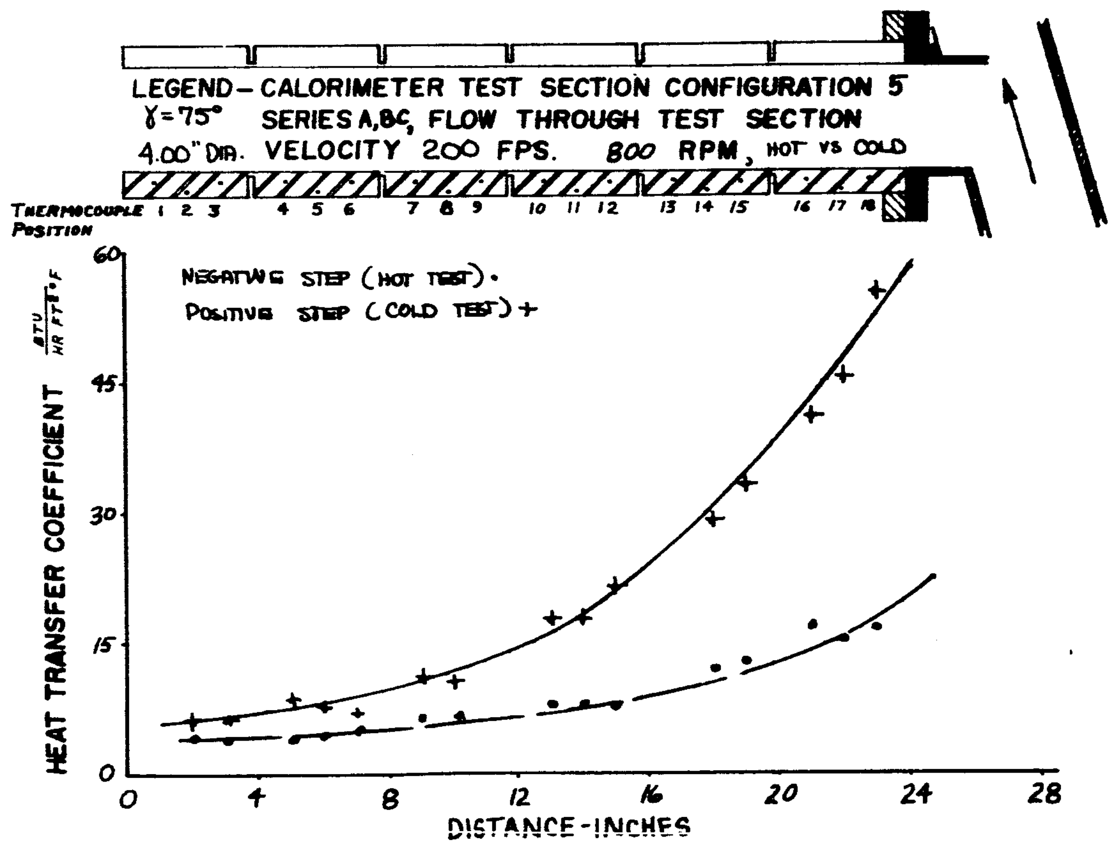


FIGURE A-121

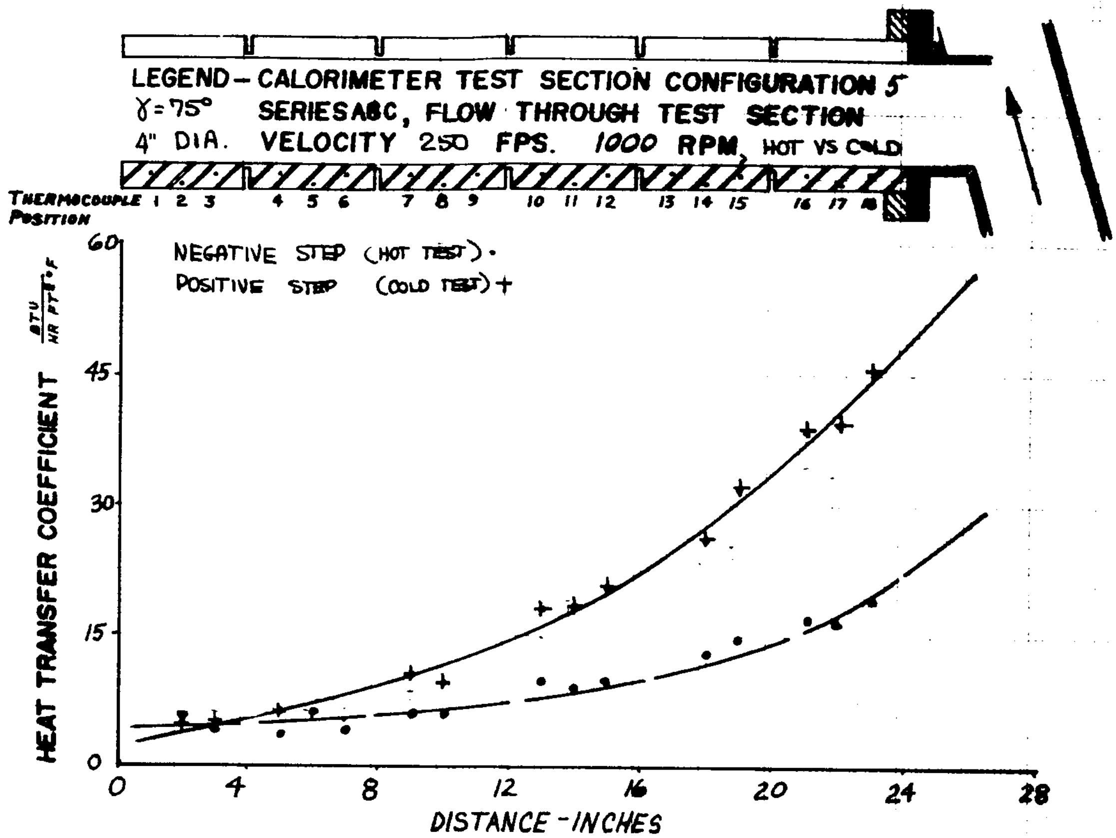


FIGURE A-122

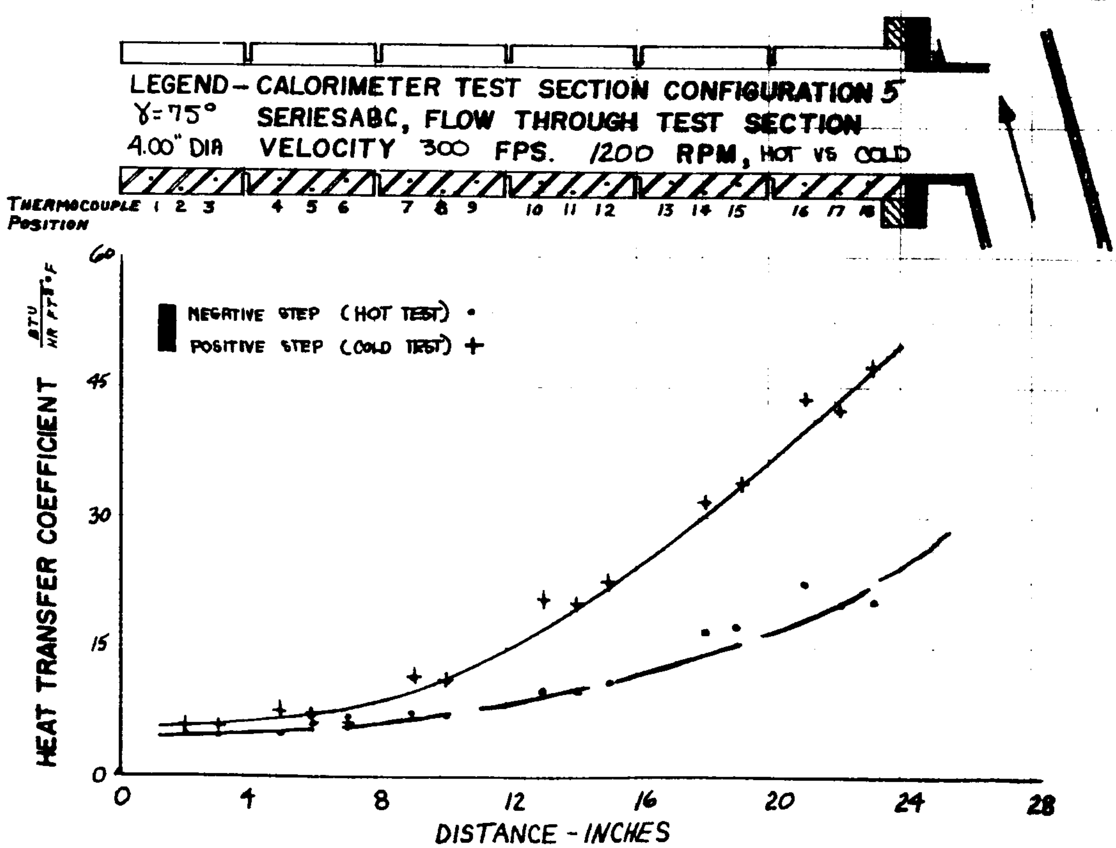


FIGURE A-123

APPENDIX B

DERIVATION OF TRANSIENT HEAT TRANSFER RELATIONS

I. Symbols

h = Film coefficient, BTU/hr. ft^2 ^oF

q = Heat transfered, BTU/hr.

M = Calorimeter element weight, lb.

A = Calorimeter element surface area, ft^2

C_p = Specific Heat (Heat Capacity), BTU/lb. ^oF

T_∞ = Free stream gas temperature, ^oF

T_o = Initial calorimeter temperature, ^oF

S = Step temperature $(T_\infty - T_o)$, ^oF

θ = Time, seconds

T = Calorimeter Temperature, ^oF
(Temperature reported by thermocouple)

II. Constants

S = Step Temperature $(T_\infty - T_o)$, ^oF

A constant value for each individual test run.

$$(MC_p/A) = 13{,}053.524, \quad \frac{\text{BTU (3600)}}{ft^2\ {}^oF}$$

This quantity is a constant for the existing calorimeter geometry and test conditions.

III. Assumptions

A. The amount of heat transfered to adjoining elements of the calorimeter is negligible and assumed to be approximately zero. (Confirmed by experiment).

B. Mass transfer does not take place.

C. Flow patterns are developed in the calorimeter test section at the instant the test is started.

IV. Relationships

Expressing the convective heat transfered through the calorimeter internal surface area in terms of film coefficient and temperature differential.

$$q = hA(T_\infty - T) \qquad \text{Eqn. 1}$$

Expressing the heat transfered by conduction in the calorimeter element in terms of time and temperature differential.

$$q = MC_p\left(\frac{dT}{d\theta}\right) \qquad \text{Eqn. 2}$$

equating yields:

$$T + \left(\frac{MC_p}{hA}\right)\left(\frac{dT}{d\theta}\right) = T_\infty \qquad \text{Eqn. 3}$$

A general solution for Eqn. 3 is

$$T = A\, e^{-\left(\frac{hA}{MC_p}\right)\theta} \qquad \text{Eqn. 4}$$

Taking the derivative of Eqn. 4

$\frac{dT}{d\theta} = -\left(\frac{hA}{MC_p}\right)A\, e^{-\left(\frac{hA}{MC_p}\right)\theta}$, substituting in Eqn. 3 yields:

$$T - \left(\frac{hA}{MC_p}\right)A\, e^{-\left(\frac{hA}{MC_p}\right)\theta}\left(\frac{MC_p}{hA}\right) = T_\infty$$

or

$$T - A\, e^{-\left(\frac{hA}{MC_p}\right)\theta} = T_\infty \qquad \text{Eqn. 5}$$

A particular solution at $\theta = 0$ and $T = T_o$ yields

$$T_o - A = T_\infty \text{ or } A = T_o - T_\infty$$

Substituting in Eqn. 5

$$T - (T_o - T_\infty)\, e^{-\left(\frac{hA}{MC_p}\right)\theta} = T_\infty$$

and replacing $(T_\infty - T_o)$ by S

$$T + S\, e^{-\left(\frac{hA}{MC_p}\right)\theta} = T_\infty$$

the temperature - time relationship is then given as

$$T = T_\infty - S\, e^{-\left(\frac{hA}{MC_p}\right)\theta} \qquad \text{Eqn. 6}$$

DATA ANALYSIS BY METHOD OF LEAST SQUARES

I. Derivation

Rearranging Eqn. 6

$$\frac{(T_\infty - T)}{S} = e^{-\left(\frac{hA}{MC_p}\right)\theta}$$

in reciprocal form

$$\left(\frac{S}{T_\infty - T}\right) = e^{\left(\frac{hA}{MC_p}\right)\theta}$$, and taking the natural logarithm

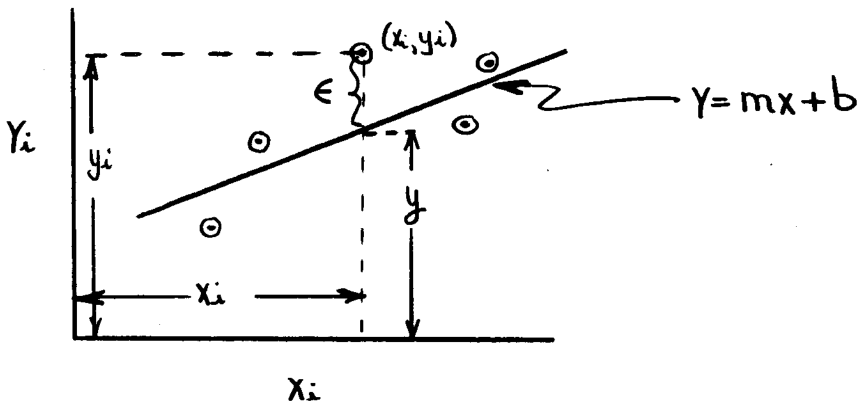
$$\ln\left(\frac{S}{T_\infty - T}\right) = \left(\frac{hA}{MC_p}\right)\theta$$

Since T_∞, h, A, M, C_p and S are constant for any particular test, the equation is of linear form if we define a new dependent variable $y = \ln\left(\frac{S}{T_\infty - T}\right)$ and independent variable $x = \theta$,

$$y = \left(\frac{hA}{MC_p}\right)x \qquad \text{or} \qquad y = \bar{M}x$$

where the slope $\bar{M} = \left(\frac{hA}{MC_p}\right)$

Consider the following data set $\sum_{i=1}^{i=n} x_i \, , \, y_i$



$$\epsilon = y_i - y = y - \bar{M}x_i \quad \text{and} \quad \Sigma\epsilon^2 = \Sigma y_i^2 + \Sigma \bar{M}^2 x_i^2 - \Sigma 2\bar{M}x_i y_i$$

Considering all data points

$$\sum_{i=1}^{i=n} \epsilon^2 = \sum_{i=1}^{n} y_i^2 + \bar{M}^2 \sum_{i=1}^{n} x_i^2 - 2\bar{M} \sum_{i=1}^{n} x_i y_i$$

Taking $\frac{d \sum_{i=1}^{n} \epsilon^2}{d\,\bar{M}} = 0$, yields $2\bar{M} \sum_{i=1}^{n} x_i^2 - 2 \sum_{i=1}^{n} x_i y_i$

Solving for $\bar{M} = \frac{\sum_{i=1}^{n} x_i y_i}{\sum_{i=1}^{n} x_i^2}$, replacing y and x

$$\bar{M} = \frac{\sum_{i=1}^{n} \ln\left(\frac{S}{T_\infty - T_i}\right)\theta_i}{\sum_{i=1}^{n} \theta_i^2}$$

Since $\bar{M} = \frac{hA}{MC_p}$ and $\frac{MC_p}{A}$ is a known constant

$$h = \bar{M}\left(\frac{MC_p}{A}\right) \quad \text{in} \quad \frac{BTU}{hr.\ ft.^2\ {}^oF}$$

II. Example

A sample data set is reduced by least squares as derived, for: Configuration 3, Series A, Thermocouple 6, at 600 RPM (ref: Project Note Book)

The following mathematical operations are necessary:

1. The test constants $T_\infty = 90.50$, $T_o = 33.25$ and $S = 57.25$ are determined from given information,
2. The calorimeter constant $\left(\frac{MC_p}{A}\right) = 13{,}053.524$ is determined from given information.
3. Test data in the form of individual values of θ (Column I) and T (Column II) are presented.
4. Subtract each entry of test data in Column II from the Test Constant T_∞.

   $(T_\infty - T)$, as shown in Column III.
5. Divide each entry of Column III into the Test Constant S.

   $S/(T_\infty - T)$, as shown in Column IV.
6. Determine the natural logarithm (base e) for each entry in Column IV.

   $\ln\left[S/(T_\infty - T)\right]$, as shown in Column V.
7. Multiply each entry in Column V by the corresponding entry in Column I.

   $\ln\left[S/(T_\infty - T)\right] \times \theta$, as shown in Column VI.

8. Sum the total of Column VI as shown.

9. Square each entry in Column II.

   $\theta \times \theta$, as shown in Column VII.

10. Sum the total of Column VII as shown.

11. Divide the Sum of Column VI by the Sum of Column VII.

$$\frac{\Sigma \ln\left[\frac{S}{T_\infty - T}\right] \cdot (\theta)}{\Sigma (\theta)(\theta)}$$

12. Multiply the resulting quotient by the calorimeter constant.

$$\frac{MC_p}{A} \cdot \frac{\Sigma \ln\left[\frac{S}{T_\infty - T}\right] \theta}{\Sigma \ \theta^2}$$

   to yield h, the heat transfer coefficient. For the sample data sheet included

   $h = 1.7152$

TABLE B-1

I θ Time in Seconds	II T Temp ^oF	III $(T_\infty - T)$ ^oF	IV $\frac{S}{T_\infty - T}$	V $\ln\left[\frac{S}{T_\infty - T}\right]$	VI $(\theta)\cdot\ln\left[\frac{S}{T_\infty - T}\right]$	VII θ^2
0	33.25	57.25	1.000	0.00000	0.00000	0
10	33.25	57.25	1.000	0.00000	0.00000	100
20	33.50	57.00	1.004	0.00399		400
30	33.50	57.00	1.004	0.00399		900
40	33.75	56.75	1.009	0.00896		1600
50	33.75	56.75	1.009	0.00896		2500
60	33.75	56.75	1.009	0.00896		3600
70	33.75	56.75	1.009	0.00896		4900
80	33.75	56.75	1.009	0.00896		6400
90	34.00	56.50	1.013	0.01292		8100
100	34.00	56.50	1.013	0.01292	1.292	10,000
110	34.00	56.50	1.013	0.01292		12,000
120	34.20	56.30	1.017	0.01686		14.400
130	34.20	56.30	1.017	0.01686		16,900
140	34.20	56.30	1.017	0.01686		19,600
					Σ = 13.3389	Σ=101,500

$$\overline{M} = \frac{\Sigma (\theta)(\ln \frac{S}{T_\infty - T})}{\Sigma (\theta)^2} = 0.0001314$$

$$h = \overline{M} \quad \frac{MC_p}{A}$$

$$h = (13,053.524)(0.0001314) = 1.7152$$

Series A - Thermocouple 6 - 600 RPM - Configuration 3 (γ = 45°)

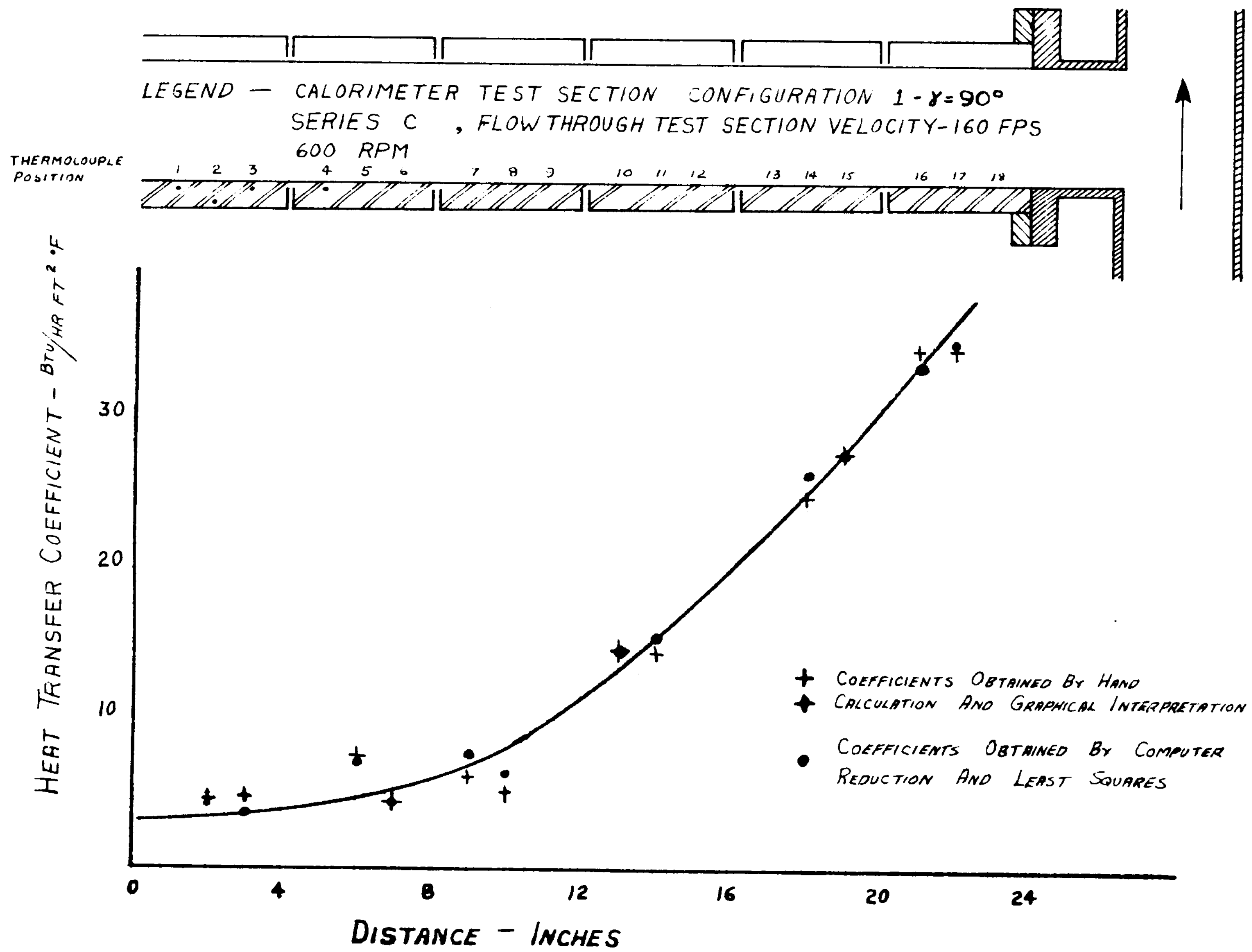


FIGURE B-1 COMPARISON OF DATA REDUCTION TECHNIQUES

DATA ANALYSIS FOR HIGH TEMPERATURE EXPERIMENTAL DATA

For the reduction of experimental data collected in the high temperature test loop the method of data analysis was modified in order to account for heat loss from the calorimeter to the ambient environment through the insulating blanket.

The heat loss to through the insulation was measured experimentally and included as data necessary for heat transfer film coefficient determination. In the following example a modified form of analysis (to the form previously specified in Appendix B) is presented. The method would be applied uniformly to room temperature or elevated temperature tests with no sacrifice of accuracy or objectivity in data reduction. However, since all room temperature testing had been completed this technique was applied only to high temperature studies. Examples of applying this technique to previously reduced room temperature data demonstrates that the technique is valid for all data assembled herein.

I. Symbols

c	Index denoting specific calorimeter
C_p	Specific Heat Formula = $0.211 + 0.6202(T_o)\ 10^4$
T_R	Temperature Recorded
$\frac{\Delta T}{\Delta \theta}$	Temperature Change per Unit Time (Due to Calorimeter Heat Loss)

II. Constants

$c = 1,\ (\frac{m}{A})_1 = 63{,}145.224$ (4 inch calorimeter)

$c = 2,\ (\frac{m}{A})_2 = 64{,}444.428$ (2 1/2 inch calorimeter)

$c = 3,\ (\frac{m}{A})_3 = 61{,}769.376$ (1 1/4 inch calorimeter)

Calorimeter constant $(\frac{m}{A})$ slightly different for each calorimeter.

$\Sigma(\theta)^2$ = 101,500.0 (Time increments identical)

III. Sample Computations

A sample data set is reduced by least squares as derived: for calorimeter 2, configuration 7, series c, thermocouple 17, at 500 RPM. The following mathematical operations are necessary:

1. The test constants are:

$$T_\infty = 80.50$$

$$T_o = 135.20$$

$$C = 2^{*} \text{(see II)}$$

$$\Sigma(\theta)^2 = \underline{101,500.0}$$

$$c_p = 0.211 + -.6202 \times 10^{-4}(T_o)$$

2. <u>compute</u> the step, s,

$$S = T_\infty - T_o = 80.50 - 135.20 = \underline{-54.70}$$

This is a constant for each test.

3. compute $\frac{mc_p}{A}$ (for c = 2)*

$$\frac{mc_p}{A} = 64444.428 \left[0.211 + 0.6202 \times 10^{-4}(T_o)\right]$$

$$\frac{mc_p}{A} = 13597.774 + 3.9968\ (135.20) = 14,138.141$$

4. Test data in the form of individual values of Θ, (Column I), and T, (Column II)(or IA) are presented.

5. Subtract each entry of test data in Column II from the test constant T_∞. $(T_\infty - T)$, as shown in Column III.

6. Divide each entry of Column III into the test constant S.

$$\frac{S}{(T_\infty - T)}$$ as shown in Column V.

7. Determine the logarithm, (base e) for each entry in Column IV.

$$\ln\left[\frac{S}{(T_\infty - T)}\right]$$, as shown in Column V.

8. Multiply each entry in Column V. by the corresponding entry in Column I.

$$\left\{\ln\left[S/(T_\infty - T)\right] \cdot \theta\right\}$$, as shown in Column VI.

9. Sum the entries of Column VI as shown.

10. Divide the sum of Column VI. by $\Sigma\ (\theta)^2$

$$\frac{\Sigma\ \left\{\ln\left[\left(\frac{S}{(T \quad - T)}\right)\right] \cdot \theta\right\}}{\Sigma\ (\theta)^2}$$

11. Multiply the resulting quotient by the calorimeter constant $\frac{\dot{m}c_p}{A}$ To yield h.

$$h = \frac{mc_p}{A} \qquad \frac{\Sigma\ \left[\ln\left(\frac{S}{T \ - \ T}\right)\right] (\theta)}{\Sigma\ (\theta)^2}$$

In the case when C = 3, (1 1/4 inch calorimeter used), the above calculations are used with an additional step to account for the loss of heat through the outside wall insulation. Columns IA and IB are added. A value of $\frac{\Delta T}{\Delta \theta}$ will be given with T_∞ and T_o. Column IA is the recorded temperatures (T_R), and Column IB is the list of $\theta(\frac{\Delta T}{\Delta \theta})$ for the respective values of θ. The values of T for Column II are arrived at by:

$$T = T_R + \theta(\frac{\Delta T}{\Delta \theta})$$ as shown in Column II.

Each case is demonstrated in the following examples:

SAMPLE DATA REDUCTION SHEET

NASA CONTRACT NAS 8-5217 Transient Heat Transfer Studies

COMMENT CARD: 79 | 80

Z | Z

______ in H_2O or RPM Δ CONFIGURATION______

$ 3,1544 $ 2,1545 (FIXED POINT)

3 30 2 x No. of θ values in table

Series THERMOCOUPLES

* (A, B, or C) *

$ 1,1532	θ(SEC) $ 1,1126	T(°F) $ 1,1326
______ T_∞		
______ T_o	0	
______ S	10.0	
______ C	20.0	
	30.0	
______ $\frac{\Delta T}{\Delta\theta}$	40.0	
	50.0	
	60.0	
	70.0	
	80.0	
	90.0	
	100.0	
	120.0	
	130.0	
	140.0	
	(*50)	(5*0)

DATE______

INITIALS______

ADDITIONAL INFORMATION FOR PREPARATION OF COMPUTER PROGRAM

<u>FOR C = 1,</u> Calorimeter No. 1 (4 inches).

Card No. 1 and 4 have the following format:

Card (1) -- RPM is given by a 3 or 4 digit number

-- CONFIGURATION is given by a 1 digit number

Card (4) -- T_∞ same as before

-- T_o same as before

-- C is given by the single digit "<u>1</u>"

-- $\frac{\Delta T}{\Delta \theta}$ = 0.0 decimal number

<u>FOR C = 2,</u> Calorimeter No. 2 (2 1/2 inches).

Cards 1 and 4 are the same as for C = 1 except on card four, C = 2.

<u>FOR C = 3,</u> Calorimeter No. 3 (1 1/4 inches).

Card (1) -- in H_2O given by 3 or 4 digit decimal number

examples: <u>15.82</u> or 5.20

CONFIGURATION -- given by 3 digit number (nondecimal)

example: <u>101</u>

Card (4) -- T_∞ same

-- T_o same

<u>3</u> C

<u>0.00714285</u> $\frac{\Delta T}{\Delta \theta}$ decimal number, 6 to 8 digits.

The quantity $\Sigma(\theta)^2$ is a constant since the time intervals are always the same for data taking.

$\Sigma(\theta)^2 = \underline{101500.}$

EXAMPLE 1

600 RPM CONFIGURATION 3 THERMOCOUPLE A-6 CALORIMETER 1

$T_\infty = 90.50^\circ F$ $T_o = 33.25^\circ F$ $S = 90.50 - 33.25 = 57.25$

$$\frac{mc_p}{A} = 13323.642 + 3.9163(33.25) = 13,453.859$$

I	II	III	IV	V	VI	VII
θ	T	$(T_\infty - T)$	$\frac{S}{T_\infty - T}$	ln IV	θ V	θ^2
Time in Seconds	$^\circ F$	$^\circ F$				
0.	34.25	57.25	1.000	0.000	0.0000	0
10.	33.25	57.25	1.000	0.000	0.0000	100
20.	33.50	57.00	1.004	0.00399	0.0798	400
30.	33.50	57.00	1.004	0.00399	0.1197	900
40.	33.75	56.75	1.009	0.00896	0.3584	1,600
50.	33.75	56.75	1.009	0.00896	0.4480	2,500
60.	33.75	56.75	1.009	0.00896	0.5376	3,600
70.	33.75	56.75	1.009	0.00896	0.6272	4,900
80.	33.75	56.75	1.009	0.00986	0.7168	6,400
90.	34.00	56.50	1.013	0.01292	1.1628	8,100
100.	34.00	56.50	1.013	0.01292	1.2920	10,000
110.	34.00	56.50	1.013	0.01292	1.4212	12,100
120.	34.20	56.30	1.017	0.01686	2.0232	14,400
130.	34.20	56.30	1.017	0.01686	2.1918	16,900
140.	34.20	56.30	1.017	0.01686	2.3604	19,600
					13.3389	101,500

$$h = \frac{mc_p}{A} \quad \frac{\Sigma \quad \theta(\ln \frac{S}{T_\infty - T})}{\Sigma(\theta)^2} = 13453.859 \quad \frac{(13.3389)}{101,500}$$

$\underline{\underline{h = 1.768}}$

This was actual weight of #1 Calorimeter, and $c_p = c_p(T) = 0.211 + 0.6202 \times 10^{-4}(T_o)$

DATA SHEET

NASA CONTRACT NAS 8-5217 TRANSIENT HEAT TRANSFER STUDIES CALORIMETER 1

COMMENTS CARD: 79 80

600 H_2O or RPM Δ CONFIGURATION 3

$ 3.1544
A Series
* (A, B, or C)

$ 2.1545 (FIXED POINT)
6 2 x No. of θ values in table. THERMOCOUPLES

$ 1,1532

90.50	T
33.25	T_o
	S
1	C
0.0	$\frac{\Delta T}{\Delta \theta}$

DATE________

INITIALS________

θ (SEC) $ 1,1126	T (°F) $ 1,1326
0	33.25
10.0	33.25
20.0	33.50
30.0	33.50
40.0	33.75
50.0	33.75
60.0	33.75
70.0	33.75
80.0	33.75
90.0	34.00
100.0	34.00
110.0	34.00
120.0	34.20
130.0	34.20
140.0	34.20
* (50)	* (50)

EXAMPLE 2

500 RPM CONFIGURATION 7 THERMOCOUPLE C-17 CALORIMETER 2

T_∞ = 80.50 T_o = 135.20 S = 80.50 - 135.20 = - 54.70

I	II	III	IV	V	VI
θ	T	$T_\infty - T$	$\frac{S}{T_\infty - T}$	$\ln\left[\frac{S}{T_\infty - T}\right]$	$\theta \cdot \left[\ln\left(\frac{S}{T_\infty - T}\right)\right]$
Time in Seconds	°F	°F			
0.	135.20	-54.70	1.0000	0.0000	0.0000
10.	135.00	-54.50	1.0037	0.00369	0.0369
20.	134.80	-54.30	1.0074	0.00737	0.1474
30.	134.60	-54.10	1.0111	0.01104	0.3312
40.	134.20	-53.70	1.0186	0.01843	0.7372
50.	133.80	-53.30	1.0263	0.02596	1.2980
60.	133.40	-52.90	1.0340	0.03343	2.0058
70.	133.20	-52.70	1.0380	0.03726	2.6082
80.	133.00	-52.50	1.0419	0.04105	3.2840
90.	132.80	-52.30	1.0459	0.04488	4.0392
100.	132.80	-52.30	1.0459	0.04488	4.4880
110.	132.20	-51.70	1.0580	0.05638	6.2018
120.	132.00	-51.50	1.0621	0.06025	7.2300
130.	131.50	-51.00	1.0725	0.06999	9.0987
140.	131.00	-50.50	1.0832	0.07992	11.1888
					Σ = 52.6952

$$\frac{mc_p}{A} = 13597.774 + 3.9968(135.20) = \underline{14138.141}$$

$$\Sigma\theta^2 = \underline{101,500}$$

$$h = \frac{mc_p}{A(\Sigma\theta^2)} \; \Sigma \; \theta\left(\ln \frac{S}{T_\infty - T}\right) \qquad = \frac{14138.141}{101500}(52.6952)$$

$$h = \underline{7.3399}$$

DATA SHEET

NASA CONTRACT NAS 8-5217 TRANSIENT HEAT TRANSFER STUDIES CALORIMETER 2

COMMENTS CARD: 79 80

500 H_2O or RPM Δ CONFIGURATION 7

$3.1544

C Series

* (A, B, or C)

$ 2,1545 (FIXED POINT)

2 x No. of 0 values in table.

17 THERMOCOUPLES

$ 1,1532

80.50	T
135.20	T_o
	S
2	C
0.0	$\frac{\Delta T}{\Delta \theta}$

θ(SEC) $ 1,1126	T (^{o}F) $ 1,1326
0	135.20
10.0	135.00
20.0	134.80
30.0	134.60
40.0	134.20
50.0	133.80
60.0	133.40
70.0	133.20
80.0	133.00
90.0	132.80
100.0	132.80
110.0	132.20
120.0	132.00
130.0	131.50
140.0	131.00
* (50)	* (50)

DATE__________

INITIALS________

EXAMPLE 3

5 in. ΔP CONFIGURATION 101 THERMOCOUPLE A-14 CALORIMETER $\frac{3}{(c = 3)}$

T_∞	T_o	
506.00	433.50	$S = 506.00 - 433.50 = 72.50$
		$\frac{\Delta T}{\Delta \theta} = 0.007786$ °F/sec

I	IA	IB	II	III	IV	V	VI
(θ)	T_R	$\theta(\frac{\Delta T}{\Delta \theta})$	$T_R+\theta(\frac{\Delta T}{\Delta \theta})$	$(T_\infty - T)$	$\frac{S}{T_\infty - T}$	$\ln(\frac{S}{T_\infty - T})$	$\theta \ln(\frac{S}{T_\infty - T})$
Time in Seconds		°F					
0.	433.50	0.0000	433.50	72.500	1.000	0.00000	0.0000
10.	434.50	0.07786	434.5779	71.422	1.015	0.01489	0.1489
20.	435.00	0.15572	435.1557	70.844	1.023	0.02274	0.4548
30.	435.34	0.23358	435.5736	70.426	1.029	0.02859	0.8577
40.	435.68	0.31144	435.9914	70.009	1.036	0.03537	1.4148
50.	435.85	0.38930	436.2393	69.761	1.039	0.03826	1.9130
60.	436.50	0.46716	436.9672	69.033	1.050	0.04879	2.9274
70.	437.00	0.54502	437.5450	68.455	1.059	0.05732	4.0124
80.	438.00	0.62288	438.6229	67.377	1.076	0.07325	5.8600
90.	438.50	0.70074	439.2007	66.799	1.085	0.08158	7.3422
100.	439.00	0.77860	439.7786	66.221	1.095	0.09075	9.0750
110.	439.34	0.85646	440.1965	65.804	1.102	0.09713	10.6843
120.	439.68	0.93432	440.6143	65.386	1.109	0.10346	12.4152
130.	440.00	1.01218	441.0122	64.988	1.116	0.10975	14.2675
140.	441.00	1.09004	442.0900	63.910	1.134	0.12575	17.6050
							$\Sigma = 88.9782$

$C = \underline{3}$ $\qquad \frac{m}{A} = \underline{61769.376}$

$$\frac{mc_p}{A} = 61768.376 \quad 0.211 + 0.6202 \times 10^{-4}(\overset{T_o}{433.5})$$

1660.695

$$= 13{,}033.127 + 3.8309(433.5) \quad = 14683.822$$

$$h = \frac{mc_p}{A} \quad \frac{\Sigma \quad \theta(\ln \frac{S}{T_\infty - T})}{\Sigma(\theta^2)} \quad = 14693.822 \quad \frac{88.9782}{101500}$$

$h = \underline{\underline{12.8814}}$

DATA SHEET

NASA CONTRACT NAS 8-5217 TRANSIENT HEAT TRANSFER STUDIES CALORIMETER 3

COMMENTS CARD: 79 80

H_2O or RPM

5.00 in H_2O Δ CONFIGURATION 101

$ 3,1544

A Series

* (A, B, or C)

$ 2,1545 (FIXED POINT)

2 x No. of θ values in table

14 THERMOCOUPLES

$ 1,1532

506.00 T_S

433.50 T_o

c = 3

$\frac{\Delta T}{\Delta \theta}$ = 0.00778571

θ (SEC) $ 1,1126	T (°F) $ 1,1326
0	433.50
10.0	434.50
20.0	435.00
30.0	435.34
40.0	435.68
50.0	435.83
60.0	436.50
70.0	437.00
80.0	438.00
90.0	438.50
100.0	439.00
110.0	439.34
120.0	439.69
130.0	440.00
140.0	441.00
* (50)	* (50)

DATE 1-2-65

INITIALS B. H. T.

TABLE B-II

FORCED CONVECTION HEAT TRANSFER COEFFICIENTS IN STRAIGHT TUBES

Using McAdams's Equation $N_{\mu\mu} = 0.027 \, (N_{Re})^{0.8} \, (N_{pr})^{1/3} \, \left(\frac{\mu}{\mu_s}\right)^{0.14}$

DIAMETER INCHES	VELOCITY 100 FPS	200 FPS	300 FPS	400 FPS	TEST TEMPERATURE
4.00	19.11	33.30	46.10	58.00	COLD - 70°F
4.00	17.97	31.30	43.40	54.50	HOT - 112°F
2.50	21.00	36.60	50.60	63.80	COLD - 70°F
2.50	19.74	34.40	47.60	59.80	HOT - 112°F
1.25	21.80	37.92	52.60	66.00	COLD - 200°F
1.25	19.52	34.00	47.10	59.30	COLD - 300°F
1.25	17.40	30.30	42.00	52.80	COLD - 500°F

(Units are: BTU/HR - ft^2 - °F)

CONVECTIVE HEAT TRANSFER COEFFICIENTS

The heat transfer coefficients for forced convection inside a tube are calculated using the McAdams Equation (1). A sample calculation is shown for the 4.00 inch diameter test section for similar free stream and wall conditions as those for which experimental data have been collected. All properties of the gas and materials will be computed at the free stream temperature and the arithmetic mean bulk temperature.

Example:

Diameter = 4.00 in $\quad T_{\infty} = 90^{o}F \quad T_{surface} = 50^{o}F$

Velocity = 100 fps: Properties evaluated at $70^{o}F$.

μ_s = 0.0435 lb/ft-hr

μ = 0.044 lb/ft-hr

k = 0.015 BTU/hr-ft ^{o}F

C_p = 0.24 BTU/lb-^{o}F

ρ = 0.075 $\frac{lb}{ft^3}$

Then, McAdams Equation

$$N_{\mu\mu} = 0.027\ (N_{RE})^{0.8}\ (N_{Pr})^{1/3}\ \left(\frac{\mu}{\mu_s}\right)^{0.14}$$

and since $N_{\mu\mu} = \frac{hD}{k}$ then,

$$h = \frac{k}{D}\ (0.027)\ (N_{RE})^{0.8}\ (N_{Pr})^{1/3}\ \left(\frac{\mu}{\mu_s}\right)^{0.14} \quad , \text{ and}$$

$$h = (0.027)\cdot\left(\frac{0.015}{0.333}\right)\cdot\left[\frac{(100)\ (3600)\ (0.333)\ (0.075)}{0.044}\right]^{0.8}\cdot \left[\frac{(0.24)\ (0.044)}{0.015}\right]^{1/3}\cdot\left[\left(\frac{0.044}{0.0425}\right)\right]^{0.14}$$

$$h = 19.11\ (BTU/hr\text{-}ft^2 - {}^{o}F)$$

APPENDIX C

EXPERIMENTAL EQUIPMENT, TECHNIQUES AND CALIBRATION

I. Experimental Equipment

Test equipment fabricated under Contract NAS 8-5217 includes two calorimeters, two flow through test sections, the infrared calorimeter heaters, the hot wire anemometer probe, the multi-channel switching assembly, the calibrator junctions, the flow visualization test sections and the hot gas test facility. Equipment purchased under Contract NAS 8-5217 included nine sub-miniature galvanometers for the Visicorder.

The schematic layout of the room temperature test apparatus assembly is shown in Figure C-1. The 4.00 and the 2.50 inch calorimeter test sections were used in this test facility for hot and cold test conditions. The 1.25 inch calorimeter was mounted in the test facility described in Figure C-2. Cold test conditions (calorimeter cooling) at a geometric parameter angle $\gamma = 90^{\circ}$ were accomplished in this facility. The wiring diagram for the switching unit with reference junction calibration is shown as Figure C-3.

II. Experimental Heat Transfer Coefficient Determination

In order to determine the heat transfer coefficient for any geometric arrangement and a particular flow through test section velocity, the following experimental procedure was carried out:

1. The experimental apparatus was started and air was circulated within the flow through test section for approximately one half hour, or until the free stream temperature was approximately 90° Fahrenheit. The calorimeter test section was wiped dry with a cloth and the slide-type valve was cleaned and lubricated. The calorimeter slide valve was closed

and the calorimeter test section was cooled to a reference temperature between 32^{o} and 35^{o} Fahrenheit. This was accomplished by filling quart size polyethylene bags with finely crushed ice and packing the calorimeter tightly with the ice bags.

2. When the calorimeter had cooled to the reference temperature, the thermocouple(s) reporting was then calibrated with the reference junction and measuring instrument (x-y recorder or Visicorder).

3. The bags of ice were removed from the calorimeter test section; the calorimeter test section was wiped dry with a towel and the dead-end portion of the test section was sealed.

4. The slide valve between the free stream flow through test section and the calorimeter test section was opened and a time history measurement of the galvanometer response to the measuring thermocouple(s) was initiated.

5. The time period for the measurement was 140 seconds.

6. The experimental curve traced by the x-y recorder or the Visicorder was then identified with respect to (a) the free stream temperature, (b) the initial temperature of the calorimeter at the start of the run, (c) the flow through test section velocity, (d) the particular thermocouples reporting, (e) the reference junction temperature, and the geometric arrangement.

7. The experimental curve was subsequently prepared for computer reduction in the following manner. The galvanometer output in millivolts was converted to temperature in degrees Fahrenheit by the use of a calibration table and curve. The values of temperature were cataloged in tabular form for the corresponding time intervals from the start of the test.

8. This data was collected in a form to be used for computer reduction (a sample of such data sheets are included in Appendix B).

9. The resultant analysis by computer utilizing the technique of least squares yields the heat transfer film coefficient in the vicinity of the measuring thermocouple.

10. When the calorimeter was being heated, steps 4 through 10 were the same. Steps 1 through 3 were modified in the following manner:

a. The infrared heater assembly was inserted in the calorimeter test section. The calorimeter test section temperature was raised to 50°F above the free stream temperature.

b. When the temperature of the calorimeter reached the desired level, the heater assembly was removed. The reporting thermocouple(s) was calibrated with the reference junction and measuring instrumentation after a short period of time to establish thermal equilibrium. The calorimeter was sealed and steps 4 through 10 were taken.

11. The experimental procedure was similar for the test data collected in the hot gas test facility. The only significant change in test routine was the increased time required for thermal equilibrium to be established. For example the 500°F free stream temperature, 300 fps free stream velocity test condition required 3 hours of operation before thermal stability was satisfactory.

III. Calibration

Consistent and continuing calibration of all measuring components in the test facilities was an important function of the experimental test technique. The flow through test section velocity profiles were examined at the beginning and at the end of every complete experimental heat transfer data body collected for a particular configuration. This was done to insure that no undetermined internal change in the test apparatus or performance of any component did take place during the collection of heat transfer data. The calibration of the flow through test section velocity provided additional information in the form of test section pressures. The velocity profiles were determined with the calorimeter section open and closed. No significant variations could be established. Turbulence screens were inserted at a location 12 diameters ahead of the test section to provide uniform gas flow characteristics.

Calibration of the measuring galvanometers was performed at the beginning of any experimental data collection and at the end of the day's testing to detect possible malfunction of the instrumentation. The design and fabrication of the calibrating circuit and switching unit were accomplished with project personnel. The switch and calibrator was compatible with the measuring instrument and the calorimeter.

The hot wire anemometer used for velocity measurements was designed by project personnel for the application within the calorimeter test section. The hot wire anemometer was fabricated in its entirety by project personnel and was calibrated in the University of Alabama low speed wind tunnel over the range of velocities corresponding to the test section velocities being investigated.

In addition to routine calibrating procedures, certain theoretical assumptions concerning heat transfer within the calorimeter were evaluated. Specifically, the heat transfer between adjoining elements of the calorimeter was assumed to be negligible. This particular assumption was examined in the following manner. One calorimeter element was isolated and all adjoining calorimeter elements were masked and insulated within the calorimeter test section. A bag of ice was laid upon the isolated element of the calorimeter. The measuring thermocouples from the element in contact with the ice and the adjoining elements were simultaneously reported through the Visicorder for a time history corresponding to a 140 seconds. The typical temperature change of the element in direct contact with the ice bag was approximately 22°F in 140 seconds; the temperature change reported in adjoining elements by measuring thermocouples, was approximately 3°F in this same time period. The temperature change reported by adjoining elements could be considered significant in the event sharp temperature gradients existed within the calorimeter test section during the test; however, since no sharp temperature gradients were determined experimentally the amount of heat transfered from one adjoining slug to another was neglected without serious error in measurement. The temperature change in adjoining slugs showed no particular variation with respect to either the radial or the longitudinal direction.

The specific calibration data and graphical presentations have been logged and are available in the project note book and will be made available to the contract representative.

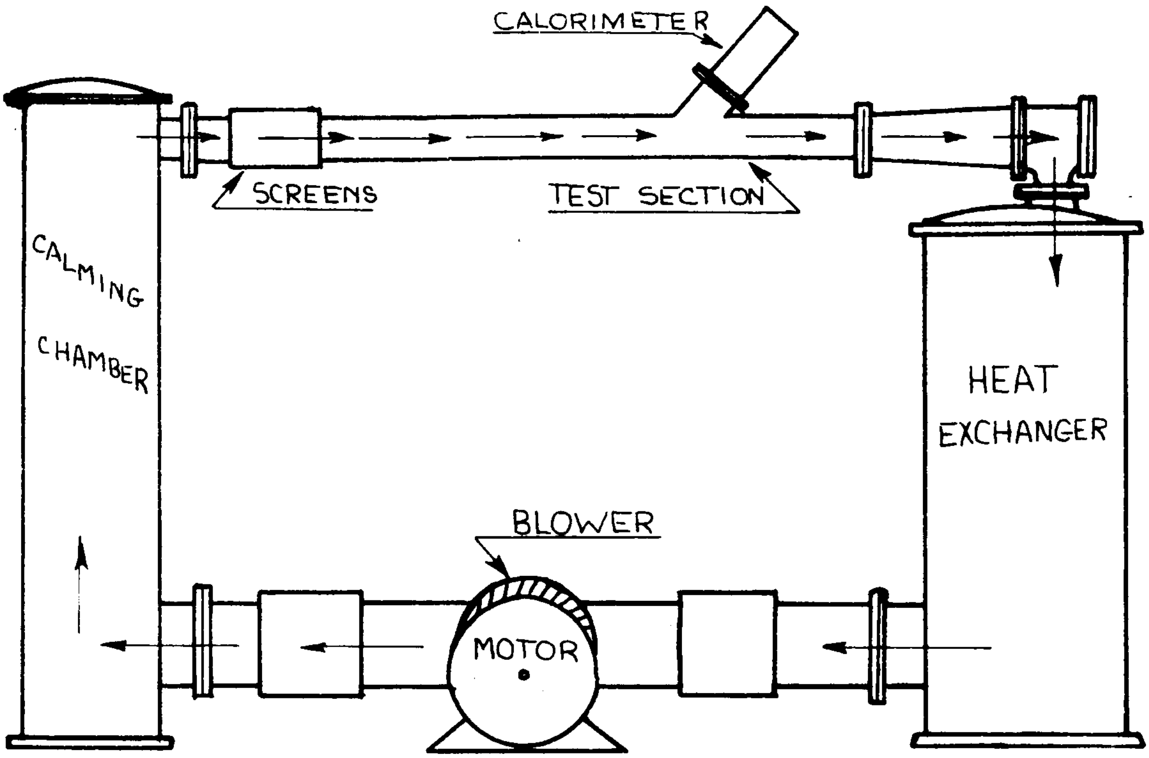


FIGURE C-1, Schematic of 2.50 and 4.00 Inch Test Facility

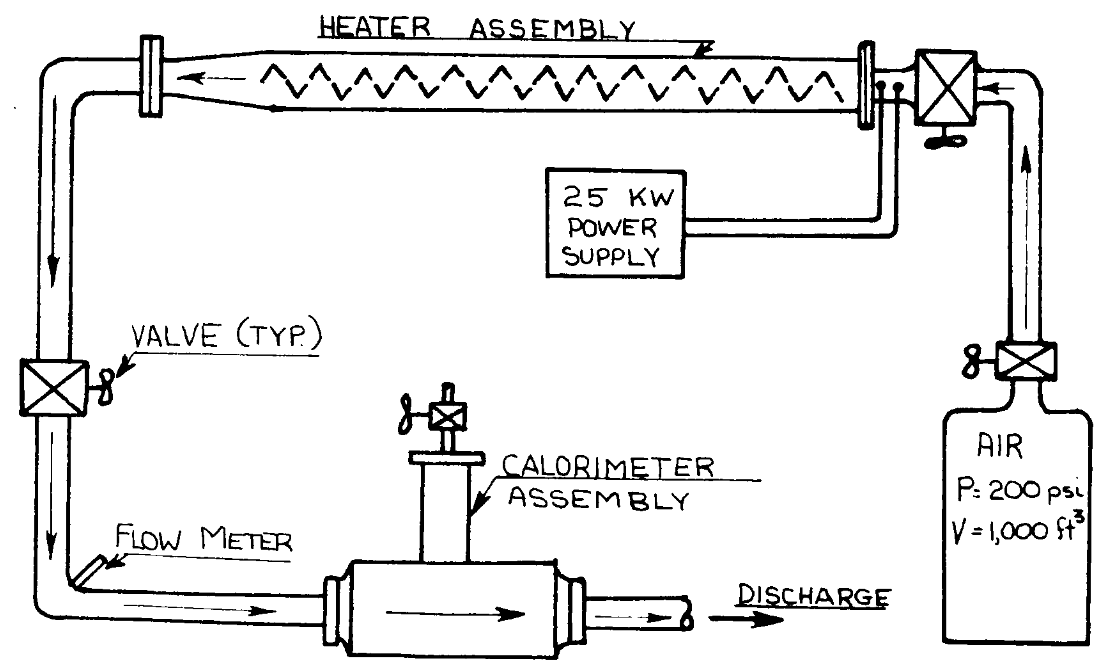


FIGURE C-2, Schematic of 1.25 Inch High Temperature Test Facility

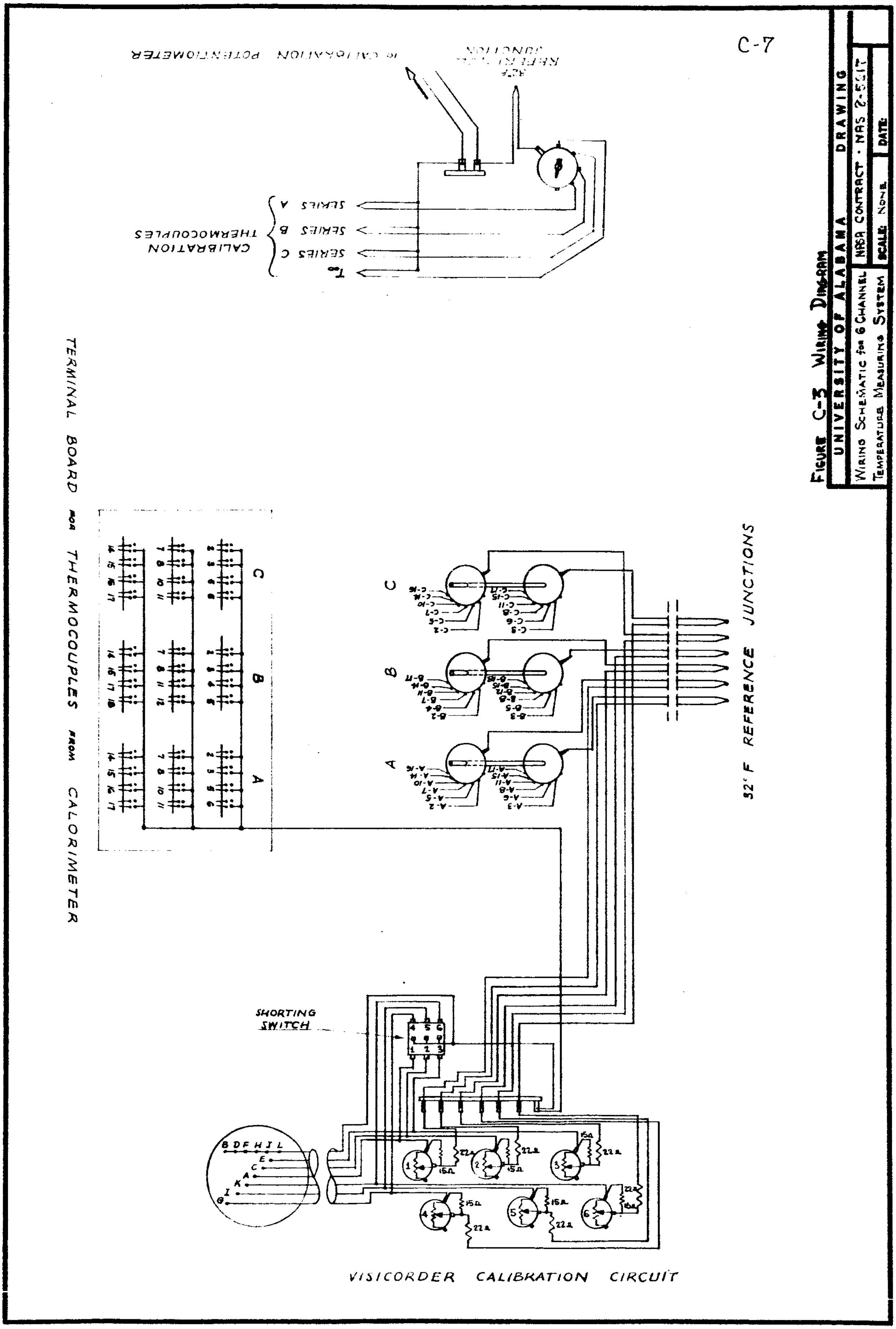


Figure C-3 Wiring Diagram

APPENDIX D

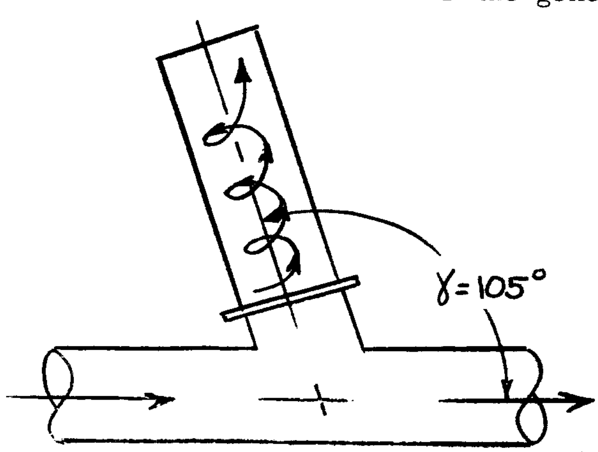
GAS BEHAVIOR AND VELOCITY MEASUREMENTS WITHIN THE CALORIMETER TEST SECTION

I. Flow Visualization

The visualization of gas flow patterns were successful for the two configurations examined (configuration 4, $\gamma = 105^{\circ}$ and configuration 5, $\gamma = 75^{\circ}$). The mechanism of gas behavior was photographed with a high speed motion picture camera.

The flow patterns were examined for a complete range of flow through test section velocities, corresponding to blower speeds from 400 to 1200 RPM.

The characteristic vortex was evident at every flow through velocity. It is of interest to note that the direction of rotation for the vortex was constant for all of the flow visualization studies attempted. The sketch in Figure D-1 illustrates the two configurations examined to date and the direction of rotation for the generated vortex.



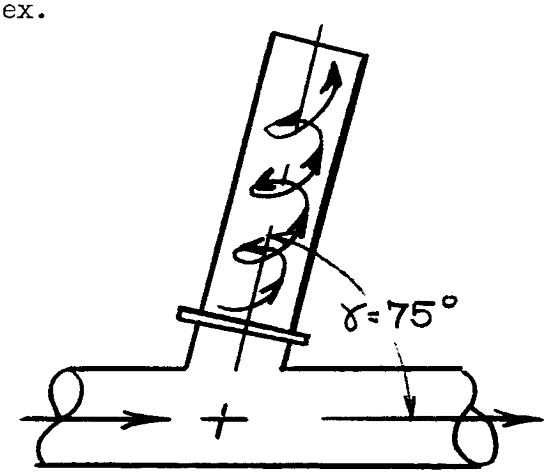


Figure D-1

II. Velocity Measurements

From the flow pattern studies it was established that the movement of gas in the calorimeter test section was essentially circumferential rather than axial as assumed initially. To attempt a correlation between the heat transfer film coefficient and the velocity of the gas moving past the elements of the calorimeter, an average velocity is computed at each longitudinal station along the calorimeter. Figure D-2 indicates the points within the calorimeter cross-section where velocity measurements were made at one-inch intervals. The planform measurement described in Figure D-2 was made at one-inch intervals, starting at the top of the calorimeter and extending into the free stream of the flow through test section. The average velocity across each element along a circumferential line is computed as :

$$V_{a_A} = \frac{V_{A_1} + V_{A_2} + V_{B_4} + V_{C_4}}{4} = \text{Average Circumferential Velocity - Series A}$$

$$V_{a_B} = \frac{V_{B_1} + V_{B_2} + V_{A_4} + V_{C_4}}{4} = \text{Average Circumferential Velocity - Series B}$$

$$V_{a_C} = \frac{V_{C_1} + V_{C_2} + V_{A_4} + V_{B_4}}{4} = \text{Average Circumferential Velocity - Series C}$$

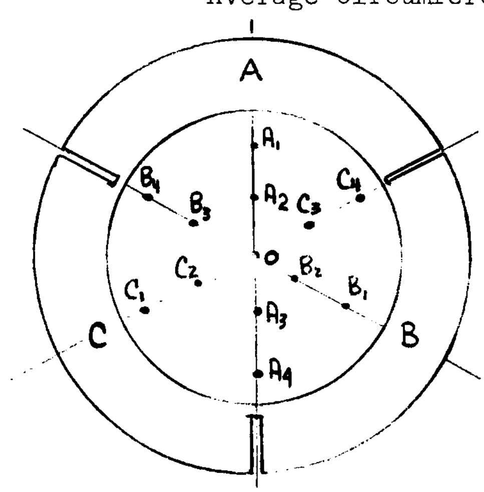


Figure D-2

The resulting values of average circumferential velocity across each element of a series are presented in Table D-1 and Figures D-2 through D-5. One geometric parameter, $\gamma = 105^{o}$ (configuration 4) at a flow through test section velocity parameter of 1000 RPM is exhibited. The large number of additional curves obtained in the identical manner for $\gamma = 75^{o}$ (configuration 5) and $\gamma = 45^{o}$ (configuration 3) are not included in this appendix for brevity. These data will be turned over to the contract representative as an addendum to the summary report.

III. Heat Transfer Data Extrapolation

A comparative correlation between average heat transfer coefficient and average circumferential velocity is presented graphically in Figure D-6 for $\gamma = 105^{o}$ (configuration 4) at a flow through velocity parameter of 1000 RPM. The curve for average heat transfer coefficient is obtained by calculating the average circumferential heat transfer coefficient. (The sum of the heat transfer coefficients in elements A, B and C, six discreet values divided by six.) This average value is then plotted along the length of the calorimeter at a point corresponding to the center of the circumferential station. Plotted on the same figure is a curve for average circumferential velocity (computed in a similar manner) versus calorimeter length.

The slopes of a straight line interpretation for this data show excellent agreement in the quiescent region and toward the intersection of both test sections. In addition, the curves of average circumferential velocity and average heat transfer coefficient plotted for each series (A, B, C) of longitudinal elements is similar to the comparison shown in Figure D-6.

From the data exhibited in Figure D-6, it would not be unreasonable to extrapolate the curve of heat transfer coefficient to the intersection of the two test sections with confidence.

Table D-1

COMPUTATION OF AVERAGE CIRCUMFERENTIAL VELOCITY WITHIN CALORIMETER TEST SECTION

AS A FUNCTION OF CALORIMETER LENGTH

$\gamma = 105^o$, Flow Through Velocity 250 fps (1000 RPM) (Reference: Figure D-2)

Position From Top (Inches)	Average Velocity Over Element A--fps					Average Velocity Over Element B--fps					Average Velocity Over Element C--fps					AVG. Circumferential Vel. fps
	A_1	A_2	B_4	C_4	AVG	B_1	B_2	A_4	C_4	AVG	C_1	C_2	B_4	A_4	AVG	
1	2.9	4.9	1.4	.8	2.5	3.5	4.8	6.0		3.7	5.5	4.2			4.4	3.5
2	3.5	4.2	1.4	.8	2.4	4.1	4.1	7.9		4.2	4.8	5.0			4.5	3.7
3	5.5	4.2	2.6	1.1	3.6	2.9	5.5	7.9		4.3	5.5	5.3			5.4	4.4
4	3.9	5.0	2.6	1.5	3.4	4.1	5.5	8.8		4.9	4.8	5.5			5.4	4.6
5	3.9	5.0	2.1	1.5	3.2	3.5	5.5	8.8		4.8	4.8	5.0			5.3	4.4
6	3.9	4.8	1.7	1.1	2.9	5.5	4.8	7.9		4.8	5.5	4.9			4.9	4.2
7	3.5	3.5	1.7	1.1	2.4	4.1	3.5	9.8		4.6	5.5	3.9			5.1	4.0
8	2.9	4.3	2.6	1.5	2.8	2.6	4.2	5.5		3.4	6.0	4.1			4.6	3.6
9	2.9	3.5	2.6	1.0	2.5	2.6	3.5	6.0		3.3	5.5	3.0			4.4	3.4
10	2.6	3.1	2.6	1.0	2.3	2.6	3.0	6.0		3.1	5.5	3.0			4.2	3.2
11	3.5	2.8	2.6	2.6	2.9	2.6	3.0	5.5		3.4	5.5	3.1			4.1	3.5
12	4.0	4.7	2.6	3.0	3.6	2.6	4.8	7.0		4.3	6.0	4.9			5.1	4.3
13	5.5	5.3	3.0	3.5	4.4	4.8	5.5	10.0		5.9	6.5	5.5			6.2	5.5
14	6.0	6.0	3.5	5.0	5.1	6.0	6.0	11.0		7.0	7.0	6.3			6.9	6.3
15	9.0	6.5	5.0	5.5	6.6	6.0	6.8	11.0		7.3	7.0	6.7			7.4	7.1
16	9.0	9.9	5.5	5.5	7.4	10.0	9.8	14.0		9.8	10.0	9.8			9.8	9.0
17	10.0	15.0	6.0	5.5	8.9	12.0	14.1	18.0		12.4	14.0	15.1			13.0	11.4
18	10.0	18.1	9.0	5.0	10.5	15.0	17.9	24.0		15.5	16.5	19.7			16.8	14.3
19	12.0	21.0	10.0	5.0	12.3	16.5	22.2	33.0		19.2	22.5	22.0			21.9	17.8
20	14.0	23.6	13.0	6.0	14.1	16.5	23.6	34.0		20.0	27.0	24.3			24.4	19.5
21	11.0	29.0	15.0	6.5	15.2	16.6	28.4	57.0		27.1	25.0	28.0			31.4	24.5
22	12.0	21.9	15.0	8.0	14.3	15.0	22.1	65.0		27.5	27.0	21.0			32.2	24.6
23	11.0	23.9	15.0	11.0	15.1	15.0	23.6	68.0		29.0	25.0	24.0			32.9	25.7
24	14.0	22.5	15.0	13.0	16.0	15.0	22.1	91.5		35.0	23.0	23.0			37.9	29.6
25	11.0	22.5	15.0	15.0	15.7	17.0	22.1	58.0		28.0	17.0	22.9			28.0	23.9
26			43.0	80.8		57.0	138.0	158.0			54.0					

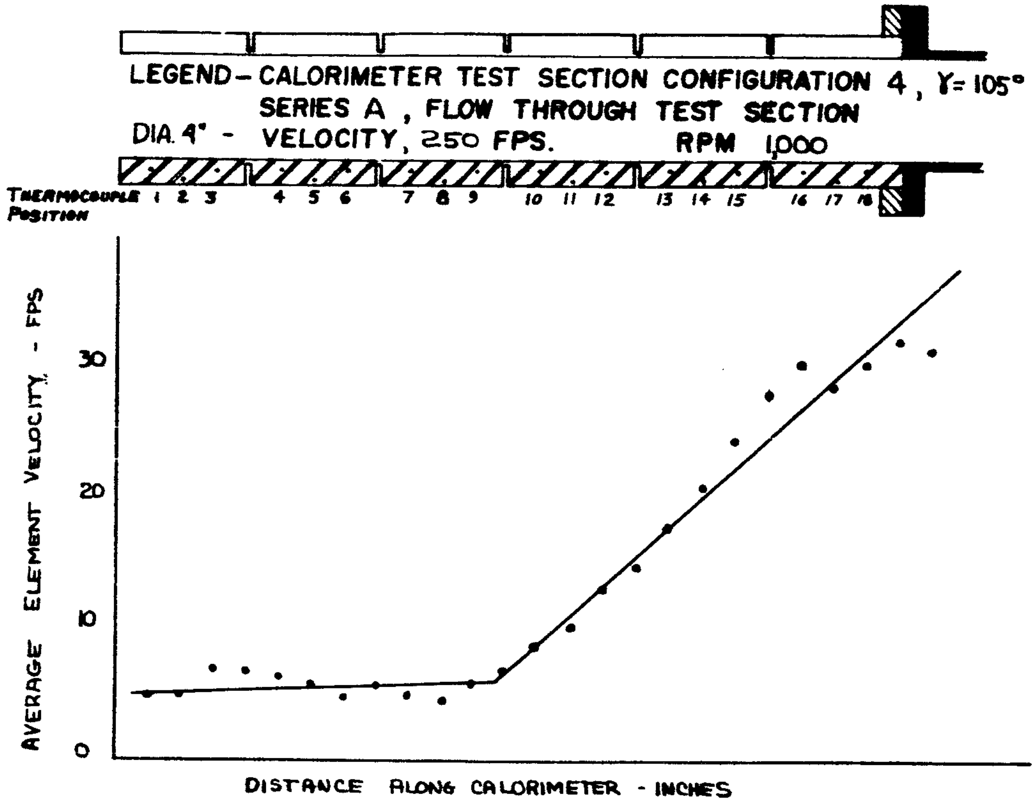


FIGURE D-3 GAS VELOCITY ACROSS CALORIMETER ELEMENTS (A)

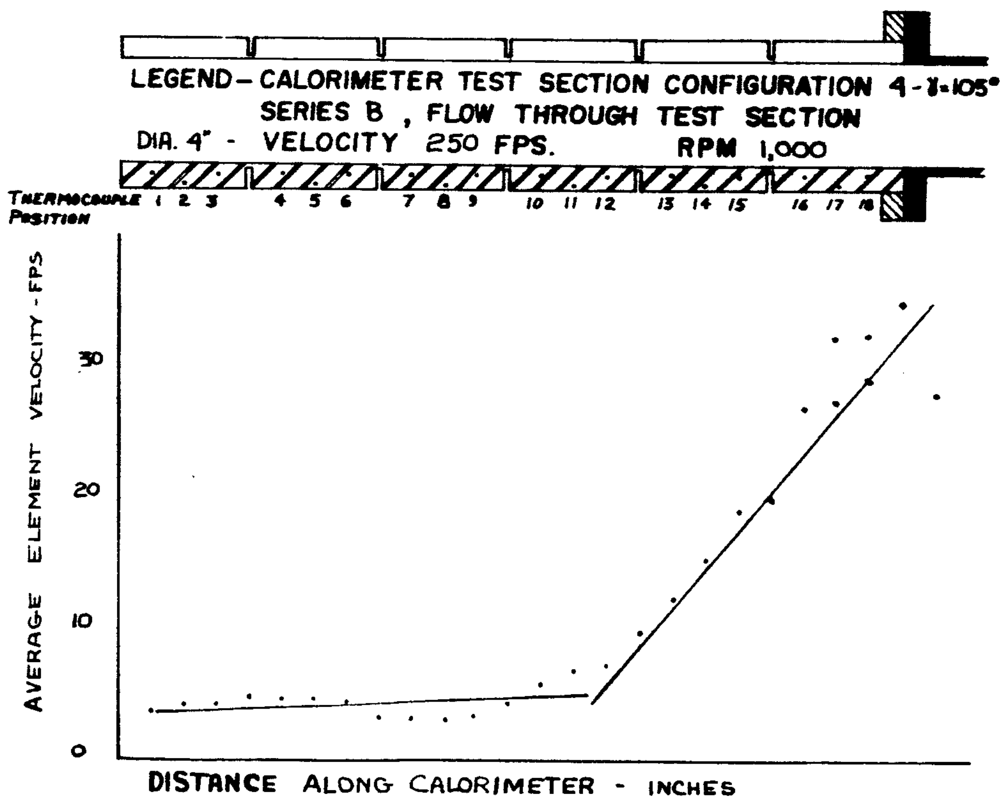


FIGURE D-4 GAS VELOCITY ACROSS CALORIMETER ELEMENTS (B)

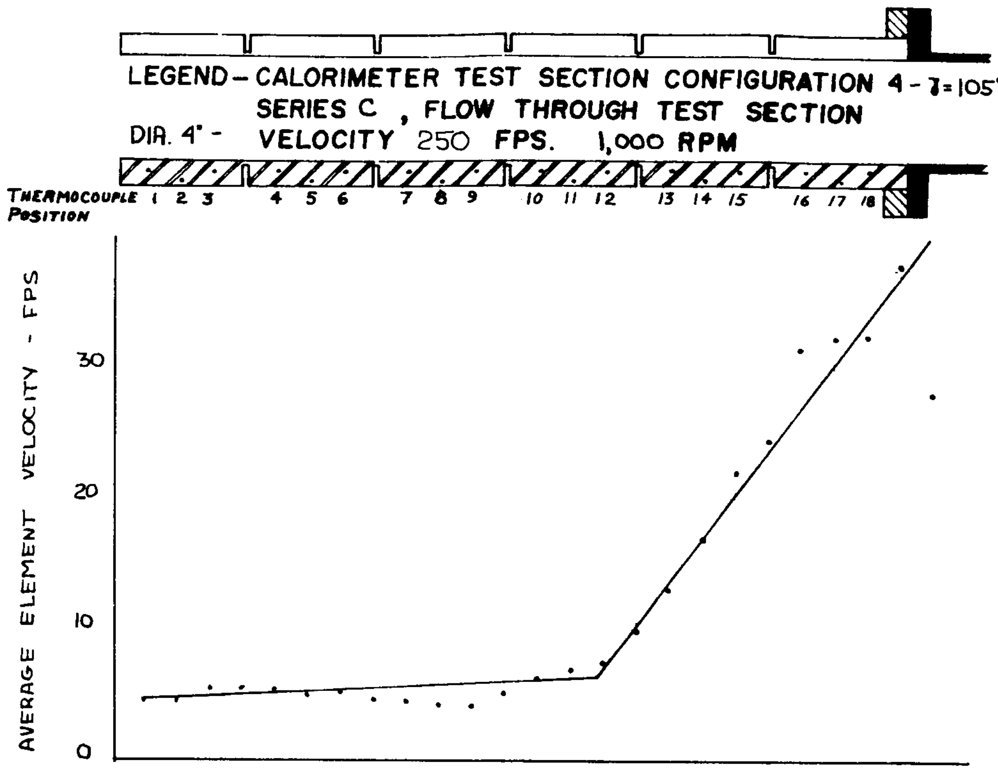


FIGURE D-5 GAS VELOCITY ACROSS CALORIMETER ELEMENTS (C)

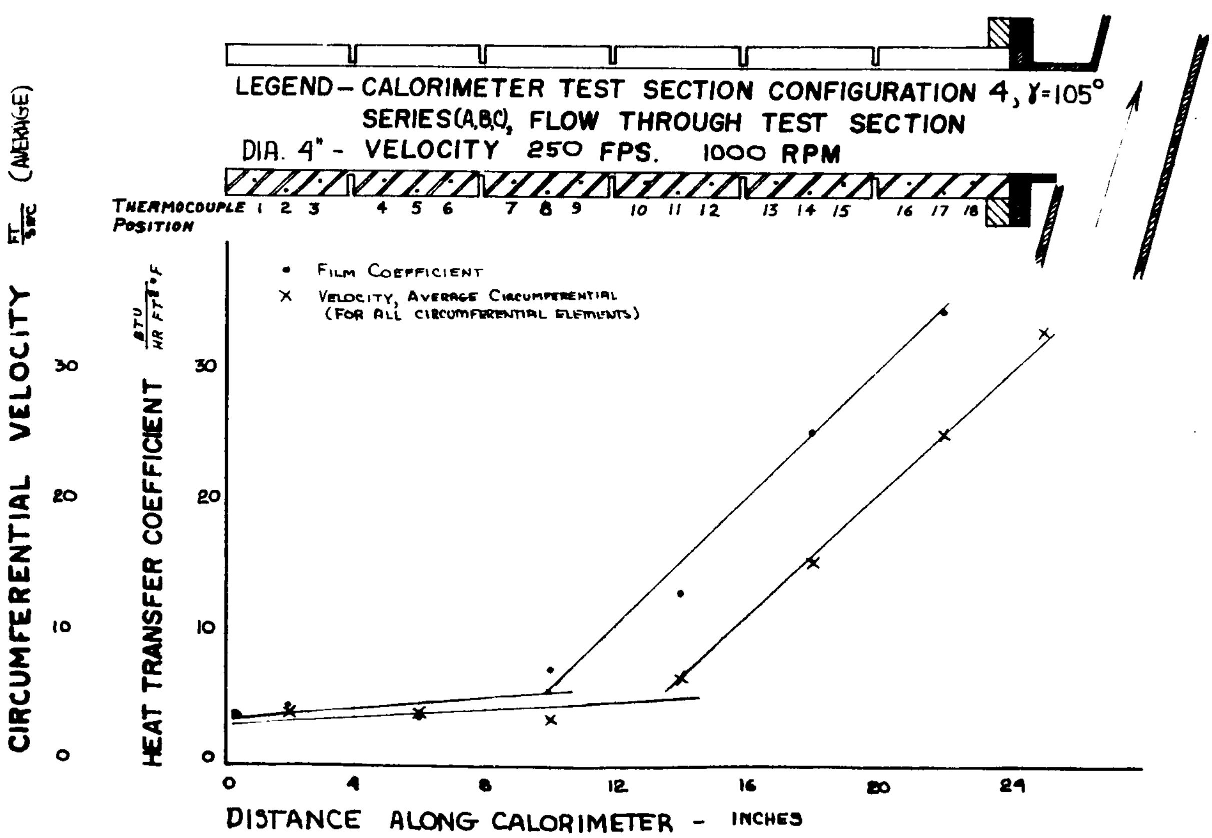


FIGURE D-6 - CALORIMETER FILM COEFFICIENT AND GAS VELOCITY VERSUS DISTANCE